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VALIDATION OF APPLICABILITY OF SUPERPAVE BINDER TEST PROTOCOL FOR PERFORMANCE GRADING OF CRUMB RUBBER MODIFIED ASPHALT BINDER

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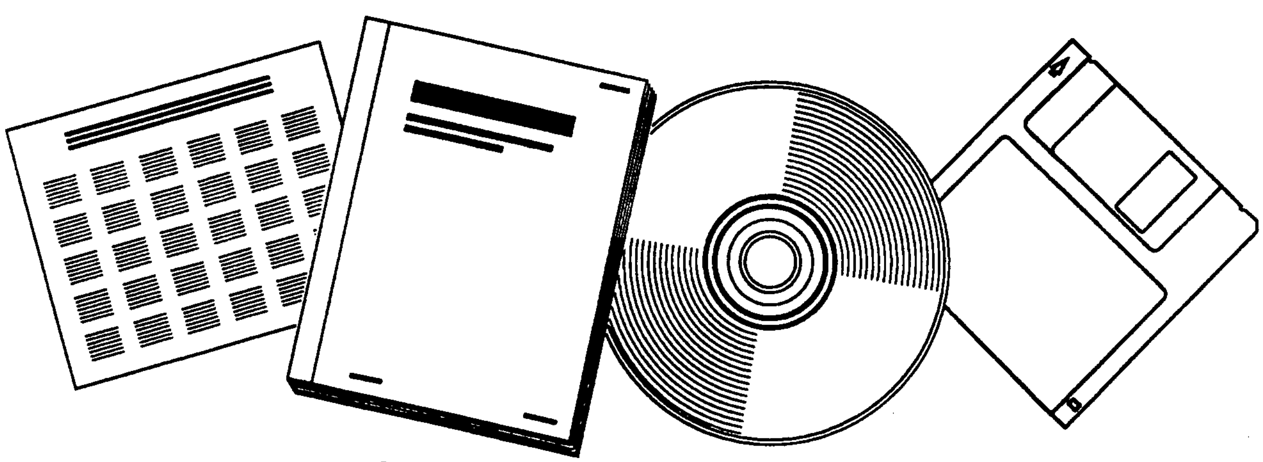

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by

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DEPARTMENT OF CIVIL ENGINEERING
NORTH CAROLINA STATE UNIVERSITY

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FINAL REPORT

RESEARCH PROJECT 23241-95-2

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16. Abstract

The Superpave™ binder specifications were primarily developed for unmodified binders. It's applicability to modified binders had not been tested. Since the use of the modified binders is increasing in the Hot Mix Asphalt (HMA) industry, it was necessary to determine whether the Superpave™ test protocols and specifications hold good for the modified binders too.

The objectives of this study was to verify the applicability of the Superpave™ test protocol to modified asphalt binders. This study was conducted using crumb rubber (40-mesh coarse graded and 80-mesh fine graded) modified asphalt binders. Two aspects of the use of crumb rubber modified binders were evaluated:

1. The applicability of the test protocol for asphalt binders to crumb rubber modified binders using DSR.
2. The characterization of crumb rubber modified binders over a range of temperatures and frequencies to evaluate the effect of crumb rubber particle size on the high temperature performance characteristics.

A 7% and 14% coarse and fine crumb rubber were blended with viscosity graded AC-20 asphalt cement to evaluate the applicability of the test protocols. Results of the analysis performed on the measured variable $G^*/\sin\delta$ indicated that the average coefficient of variation for the different specimen thicknesses and replicate testing was 6.2% and 6.5%, respectively. In general, the crumb rubber particles (i.e. coarse rubber versus the fine rubber) did not affect the performance grading of the modified binders used in this study.

This study indicated that 7% crumb rubber modification increased the high temperature performance grade of the binder by one higher grade; whereas, 14% crumb rubber modification increased the high temperature performance grade by two higher grades. The higher temperature performance characteristics of the unmodified and modified binders having the same performance grading was found to be similar. Test results indicate that the Superpave™ test protocols are applicable to modified binders used in this study.

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Executive Summary

This study investigated two aspects of the performance related Superpave™ binder specification methodology -- applicability of the DSR to crumb rubber modified binders, and effect of crumb rubber particle size and concentration on the higher temperature performance grading of asphalt cements commonly used in North Carolina. In addition, physical characteristics of 5 more performance graded unmodified and modified binders were evaluated over a range of frequencies and temperature.

The hypothesis investigated was that, if the crumb rubber particle size and concentration interfered with the DSR test measurements, varying the film thickness of the binder specimen should significantly affect the measured properties. In order to validate this hypothesis, two binder film thicknesses were used. At low temperature, 2 mm and 4 mm film thicknesses were evaluated. For medium and high temperatures, 1 mm and 2 mm film thicknesses were evaluated.

Test results indicated that the overall average coefficient of variation due to the use of different specimen film thickness and replicate testing were 6.2% and 6.5%, respectively. Based on these results, it was concluded that for the crumb rubber particle size and concentrations used, the AASHTO TP5 test protocol is applicable to the modified binders used in this study.

Unmodified and modified binders were also characterized over a range in frequency and temperature using the AASHTO TP5 test protocol and the DSR research package. In general, test results indicate that the variability due to replicate testing using the research package is much higher than the Superpave™ specified DSR test package. Much of the variability was observed to be associated with the low temperature testing (use of the 8 mm diameter spindle size, and temperatures below 24°C). The crumb rubber modified RTFO and PAV aged binders, at low temperatures were so stiff that testing could not be conducted at a reasonable strain value, due to the torque limitation of the DSR.

Based on the experience obtained from this study, it is the opinion of the authors that much of the variation in test results can be minimized as follows:

1. Operator training and experience. It was observed during the duration of this study that the variability in test results systematically reduced as the DSR operator gained more training and experience in setting up specimens, especially for the 8 mm diameter specimens.
2. Variability seemed to reduce with the use of silicon molds supplied by the Asphalt Institute for preparation of the test specimens.
3. AASHTO TP5 test protocol suggest a range of strain (or stress) levels which may be used for testing. Test results indicate that at any temperature, a sufficiently high strain level (in the linear viscoelastic limit defined by the protocol) must be used in order to get repeatable results. Some modified PAV aged binders at low temperatures could not be tested at acceptable strain levels to get any meaningful results.

Specific conclusions based on the results of this study are as follows:

1. The coefficient of variation for test results increased slightly for the crumb rubber modified binders used in this study. Based on the overall coefficient of variation of approximately 6.5% for the unmodified and modified binders tested, it appears that the AASHTO TP5 test protocol is applicable to the modified binders used in this study.
2. The coefficient of variation obtained when using the DSR research package is much higher as compared to the DSR Superpave™ test package.
3. For both AC-20 and AC-10 asphalts, addition of 7% crumb rubber (coarse and fine crumb rubber) produced one higher performance grade jump; i.e., from PG 64-y and PG 58-y to PG 70-y and PG 64-y, respectively.
4. For AC-20 asphalt, addition of 14% crumb rubber (coarse and fine rubber) produced two higher performance grade jump; i.e., from PG 64-y to PG 76-y, respectively.

5. For AC-10 asphalt cement, addition of 14% coarse rubber produced three higher performance grade jumps; i.e., from PG 58-y to PG 76-y, whereas the addition of 14% fine rubber produced a two grade jump from PG 58-y to PG 70-y.
6. Except for one binder, the high temperature performance grading of the PG binders were confirmed. The PG 70-22 binder failed to achieve the 1 kPa value for the $G^*/\sin\delta$, although it did barely meet the 2.2 kPa value after RTFO aging.
7. The addition of 7% coarse and fine crumb rubber produced a one higher performance grade jump over the base asphalt cements. Results suggest that as low as 5% crumb rubber modification will have a similar effect on the performance grading of both AC-20 and AC-10 modified binders. Similarly, as little as 10% crumb rubber will have the same effect of increasing performance grade by two jumps as compared to the 14% used in this study.
8. In the high temperature range (more than 42°C) the behavior of different unmodified and modified binders appear to be similar, especially the modified binders containing the same base asphalt.
9. In the intermediate/low temperature range, these same binders appear to behave differently. The PG 76-22 Multi-grade and SBS modified binders having same low temperature grade (-22°C) show different characteristics. Crumb rubber modified binders seems to approach the stiffness of the base asphalt at lower temperatures.

Relationships between the limiting temperature (temperature at which the $G^*/\sin\delta$ value of 1 kPa is reached) and the fine and coarse crumb rubber concentrations were developed. These relationships can be used as a guide to specify and produce crumb rubber modified binders which meet specific performance grading requirements. Based on the results of this study, it appears that for all conditions being the same, an AC-10 asphalt cement modified with 5% to 7% crumb rubber will perform equal to or better than the AC-20 unmodified binder over a range of temperature.

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Notations

CR	40 mesh (coarse) crumb rubber
CV	Coefficient of variation
δ	Phase angle
e	base of natural logarithm
FR	80 mesh (fine) crumb rubber
G^*	Dynamic shear modulus
Ln	Natural logarithm
PAV	Pressure aging vessel
PG	Performance graded
RTFO	Rolling thin film oven
s	Sample standard deviation
Var	Sample variance s^2

1. Introduction

The Strategic Highway Research Program (SHRP) Superpave^{TM} mix design and analysis system was designed to quantify and maximize the performance of asphalt binders in reducing the occurrence of pavement distresses -- permanent deformation, fatigue and low temperature cracking. Present specification testing protocol and performance-grading of asphalt binders were developed primarily for conventional asphalts. In the asphalt paving industry, there appears to be some concern about the applicability of these specifications and test protocols to modified asphalt binders.

This study was initiated in 1994 by the North Carolina Department of Transportation (NCDOT) to investigate the applicability of the Superpave^{TM} binder testing equipment for performance related specification of asphalt binders containing modifiers. Of particular interest to the NCDOT -- due to the ISTEA mandate (Intermodal Surface Transportation Efficiency Act, 1991) -- was the inclusion of the crumb rubber as a modifier in asphalt mixes.

This study investigated two aspects of the performance related Superpave^{TM} binder specification methodology -- the applicability of the dynamic shear rheometer (DSR) to crumb rubber modified binders, and the effect of crumb rubber particle size and concentration on the higher temperature performance grading of asphalt cements commonly used in North Carolina.

In addition, physical characteristics of 5 more PG (Performance Graded) binders which were to be used for the SPS-9A study in North Carolina, were also evaluated over a range of frequencies and temperature.

1.1 Objectives and Scope of the Study

The objectives of this study were the following:

1. To examine the applicability of the current Superpave^{TM} DSR testing protocol developed for unmodified binders to crumb rubber modified asphalt binders. Evaluated within this

objective was the effect of stress/strain level, asphalt specimen film thickness and test repeatability.

2. To study the effect of crumb rubber gradation and amount (concentration) on the high temperature performance grading of asphalt cements commonly used in North Carolina.
3. To develop a data base of physical properties such as dynamic shear stiffness and phase angle for the modified asphalt binders over a wide range in temperatures and frequencies.
4. Based on the results, recommend necessary changes if required for application of Superpave™ performance-based asphalt binder specifications for modified asphalt binders.

1.2 Research Approach and Experiment Design

The Superpave™ binder specifications and the measurements upon which they are based were designed to provide performance-related properties of the binder that can be related in a rational manner to pavement performance. The performance-related binder specification was based primarily on the rheological properties (stiffness and phase angle) of the binder for a specific combination of traffic loading and environmental conditions. These binder specifications shown in Figure 1-1 use the designation **PG x-y** [1,2, 3,4] where:

PG	stands for Performance Graded,
x	designates the high pavement design temperature - average 7 day maximum, and
y	designates the low pavement temperature - minimum design temperature.

Superpave™ binder specifications for fatigue and rutting distresses, corresponding to the intermediate and high temperatures, respectively, are evaluated using the dynamic shear rheometer (DSR). The DSR essentially measures the stiffness (G^*) and phase angle (δ) of a thin layer of asphalt binder placed between two parallel circular plates. The bottom plate is kept fixed and the top plate is oscillated at a constant stress or strain at specified frequency and temperature. The shear stiffness and phase angle are evaluated using the stress-strain response of the material. Superpave™ binder specifications based on test measurements at an oscillatory frequency of 10 radians per

Performance Grade	PG 46			PG 52							PG 58					PG 64					
	-34	-40	-46	-10	-16	-22	-28	-34	-40	-46	-16	-22	-28	-34	-40	-10	-16	-22	-28	-34	-40
Average 7-day Maximum Pavement Design Temperature, °C [a]	<46			<52							<58					<64					
Minimum Pavement Design Temperature, °C [a]	>-34	>-40	>-46	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
Original Binder																					
Flash Point Temp, T48: Minimum °C	230																				
Viscosity, ASTM D 4402: [b] Maximum, 3 Pa•s (3000 cP), Test Temp, °C	135																				
Dynamic Shear, TP5: [c] G*/sin δ, Minimum, 1.00 kPa Test Temperature @ 10 rad/s, °C	46			52							58					64					
Rolling Thin Film Oven (T 240) or Thin Film Oven (T 179) Residue																					
Mass Loss, Maximum, %	1.00																				
Dynamic Shear, TP5: G*/sin δ, Minimum, 2.20 kPa Test Temp @ 10 rad/sec, °C	46			52							58					64					
Pressure Aging Vessel Residue (PP1)																					
PAV Aging Temperature, °C [d]	90			90							100					100					
Dynamic Shear, TP5: G*sin δ, Maximum, 5000 kPa Test Temp @ 10 rad/sec, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Physical Hardening [e]	Report																				
Creep Stiffness, TP1: [f] S, Maximum, 300 MPa m-value, Minimum, 0.300 Test Temp, @ 60 sec, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
Direct Tension, TP3: [f] Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

Figure 1-1 Superpave^{TM} performance grade binder specifications (AASHTO MP1)

second (1.59 Hz) impose the following specification criteria for intermediate and high temperatures:

1. stiffness value $G^*/\sin\delta$ greater than 1 kPa at the anticipated maximum 7 day average pavement temperature, evaluated on the unaged binder;
2. stiffness value $G^*/\sin\delta$ of the binder after RTFO (Rolling Thin Film Oven) aging greater than 2.2 kPa at the anticipated maximum 7 day average pavement temperature; and
3. stiffness value $G^*\sin\delta$ of the binder after RTFO and PAV (Pressure Aging Vessel) aging less than 5000 kPa at the average pavement temperature.

This investigation was conducted in two phases. Task A evaluated the applicability of the Superpave™ testing protocol for crumb rubber modified binders. Task B fully characterized the crumb rubber and other modified binders over a range in temperatures and frequencies. Significant test variables considered for both tasks of this study are presented in the following sections.

1.2.1 Task A -- Verification of Applicability of Superpave™ Protocol to Crumb Rubber Modified Binders

The main purpose of this task was to determine whether the crumb rubber particle size and its concentration in the asphalt binder affected test results when tested using the Superpave™ DSR testing equipment and protocol. In order to evaluate this effect, an AC-20 asphalt cement was selected and modified with crumb rubber as shown in Table 1-1. Table 1-2 summarizes the significant test variables for Task A.

Table 1-1 Material variables for Task A

Variables	Level of Treatment	No. Treatment Level
Asphalt Source: Asphalt Grades (viscosity graded):	1 AC-20	1 1
Crumb Rubber: Source: Particle size: Concentration by wt. of asp. cement:	 1 40 and 80 mesh 7 and 14%	 1 2 2

Table 1-2 Verification of applicability of Superpave™ test protocol to crumb rubber modified binder, significant test variables for Task A

Test Variables	Level of Treatment	No. Treatment Level
Aging	Unaged, RTFO and PAV	3
Stress/Strain Amplitudes	2, 5, 10, 15 & 20% shear strain	5
Temperatures	12, 42, 70°C	3
Asphalt Film Thickness:	2 mm & 4 mm @ 12°C 1 mm & 2 mm @ 42 & 70°C	2
Temperature Equilibrium Time	6 minutes	1
Preconditioning Cycles	AASHTO TP5	1
Spindle diameter	AASHTO TP5	1
Test Frequency	10 rad/sec (1.59 Hz)	1
Repeats	Full replication	2

1.2.2 Task B -- Binder characterization using Dynamic Shear Frequency Sweep

The main purpose of this task was to characterize the modified and unmodified binders over a range of frequencies and temperatures. Fifteen binders were evaluated in unaged, RTFO aged, and PAV aged conditions. This resulted in a total combination of 45 aged and unaged binders. Tables 1-3 and 1-4 show the materials and test variables used for Task B, respectively.

Table 1-3 Material variables for Task B

Variables	Level of Treatment	No. Treatment Level
Asphalt Source: Asphalt Grades (viscosity graded):	1 AC-10 and AC-20	1 2
Crumb Rubber for AC-10 & AC-20: Particle size: Concentration by wt. of asp. cement:	 40 and 80 mesh 7 and 14%	 2 2
Other binders evaluated (SPS-9A Materials):		
PG64-22	1	1
PG70-22	1	1
PG76-22 SBR Modified	1	1
PG76-22 SBS Modified	1	1
PG76-22 Multi-Grade	1	1

Table 1-4 Binder characterization using dynamic shear frequency sweep, significant test variables for Task B

Test Variables	Level of Treatment	No. Treatment Level
Aging	Unaged, RTFO and PAV	3
Stress/Strain Amplitudes	Selected Based on Superpave Protocol and/or Task A	1
Temperatures	Range 6-76°C (6, 12, 24, 30, 42, 52, 58, 64, 70, 76)	10
Asphalt Film Thickness	Selected Based on Superpave Protocol and/or Task A	1
Test Frequency	Range 0.6 to 125 rad/sec (0.1, 0.15, 0.2, 0.5, 1, 2, 5, 10, 15, & 20 Hz)	10
Spindle diameter	AASHTO TP5	1
Temperature Equilibrium Time	6 minutes	1
Preconditioning Cycles	AASHTO TP5	1
Repeats	Full replication	2

1.2.3 Tests Conducted at NCDOT Materials and Test Unit

Partial testing of the modified binders was carried out at the NCDOT Materials and Test Unit (M&T Unit) to compare the test results with those conducted at the NCSU Laboratory. The DSR testing was conducted on the AC-20 asphalt modified with 7% coarse (40-mesh) and 7% fine (80-mesh) rubber. These binders were tested in their unaged, RTFO aged and PAV aged conditions. In addition to the DSR testing, these modified binders were also tested using the Bending Beam Rheometer (BBR) to determine their low temperature properties. The viscosity of the AC-20 virgin asphalt, AC-20 treated (processed) asphalt, and AC-20 asphalt modified with 7% and 14% coarse and fine rubber was determined using the Rotational Viscometer to evaluate the flow characteristics of the asphalt binders.

Table 1-5 shows the material variables for the tests conducted at the NCDOT M&T Unit. Test results are tabulated and discussed in section 3.2.

Table 1-5 Material variables for tests conducted by NCDOT M&T Unit

Variables	DSR and BBR Test		Rotational Viscometer	
	Level of Treatment	No. Treatment Level	Level of Treatment	No. Treatment Level
Asphalt Source: Asphalt Grades (viscosity graded):	1 AC-20	1 1	1 AC-20	1 1
Crumb Rubber: Source: Particle size: Concentration by wt. of asp. cement:	 1 40 and 80 mesh 7 %	 1 2 1	 1 40 and 80 mesh 7 %	 1 2 1

2. Materials Used

The materials used in this study were obtained from the Materials and Test Unit of the North Carolina Department of Transportation. For the purpose of this study, two asphalt cements commonly used in North Carolina were used. These were viscosity graded AC-20 and AC-10 Citgo asphalts. The base asphalts were blended with a 40-mesh coarse graded (CR--Coarse Rubber) crumb rubber and an 80-mesh fine graded (FR--Fine Rubber) crumb rubber. Average gradation test results for the CR and FR are given in Table 2-1 and Figure 2-1. The results represent an average of at least 3 tests on each of the crumb rubber sizes. It may be noted that during gradation testing, small clumps (balls) of fibers were observed on the coarser sieve sizes.

Table 2-1 Gradation test results for 40-mesh and 80-mesh crumb rubber

Sieve Size, mm	US Standard Sieve	% Passing 40-Mesh Coarse Rubber (CR)	% Passing 80-Mesh Fine Rubber (FR)
1.18	#16	100	100
0.60	#30	72	99
0.425	#40	34	-
0.30	#50	11	80
0.18	#80	-	15
0.15	#100	3	3
0.075	#200	0	0
pan		0	0

The AC-20 and AC-10 asphalt cements were blended with CR and FR with 7-percent and 14-percent concentration (rubber content by weight of asphalt cement) to produce the various crumb rubber modified binders. A wet blending procedure was used to manufacture the modified binders. In this procedure, 1 gallon batch of the base asphalt was pre-heated to about 135°C to 145°C.

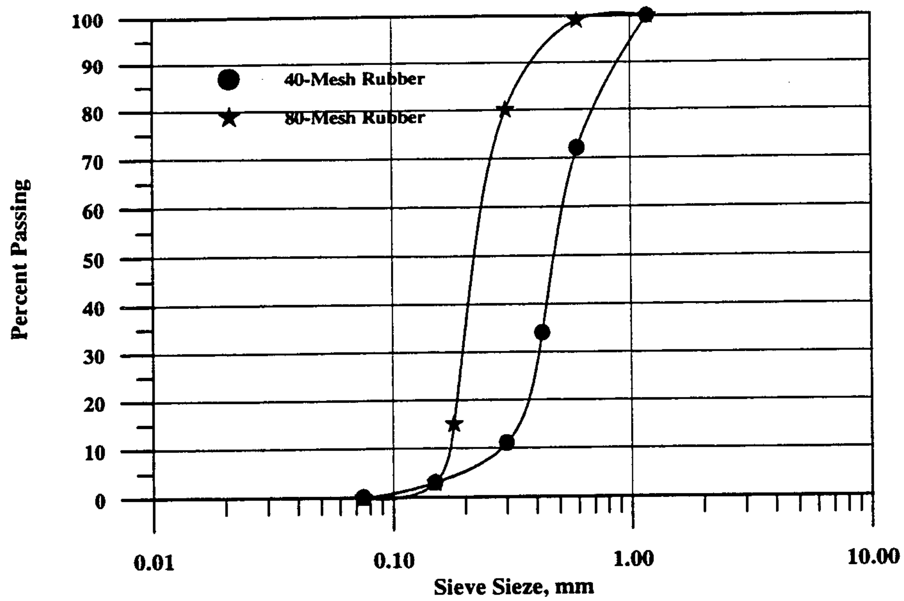

Figure 2-1 Gradation test results for 40-mesh and 80-mesh crumb rubber

The asphalt was continuously stirred with the help of a mechanical mixer and the 7 and 14-percent of crumb rubber (by weight of asphalt cement) was gradually added in smaller amounts. Gradual addition of the rubber was necessary to allow the asphalt to "burp" and release entrapped air bubbles. Once the required quantity of rubber was added, mixing process was continued at medium shear speed for 90 minutes, following which the blended binder was immediately transferred to smaller 3 oz. and 8 oz. cans for testing. The blended binder was observed to have a coarse texture after production with a viscosity increase, but no formal measurements of viscosity were made. Some penetration testing was done on the binders. The results are presented in section 3.1.

No particular difficulties were encountered in mixing the required amount of crumb rubber with the asphalt cement. The crumb rubber was blended without addition of any extender oil or catalysts. Because the asphalt cement in the modified binders was subjected to heating and mixing treatment, 1 gallon batches of AC-20 and AC-10 base asphalt cements were also subjected to the same 90 minutes mixing process. These are referred to as AC-20 and AC-10 ***Processed*** asphalt cements. The total of 10 modified and processed binders produced were as follows:

1. AC-20 Processed (Base asphalt processed for 90 minutes)
2. AC-20+7% CR (7-percent 40-mesh coarse rubber by wt. of asphalt cement)
3. AC-20+14% CR (14-percent 40-mesh coarse rubber by wt. of asphalt cement)
4. AC-20+7% FR (7-percent 80-mesh fine rubber by wt. of asphalt cement)
5. AC-20+14% FR (14-percent 80-mesh fine rubber by wt. of asphalt cement)
6. AC-10 Processed (Base asphalt processed for 90 minutes)
7. AC-10+7% CR (7-percent 40-mesh coarse rubber by wt. of asphalt cement)
8. AC-10+14% CR (14-percent 40-mesh coarse rubber by wt. of asphalt cement)
9. AC-10+7% FR (7-percent 80-mesh fine rubber by wt. of asphalt cement)
10. AC-10+14% FR (14-percent 80-mesh fine rubber by wt. of asphalt cement)

In addition to the modified binders listed above 5 more PG graded binders were characterized over a range of frequencies and temperature. These base and polymer modified binders were as follows:

1. PG 64-22 (Citgo)
2. PG 70-22 (Citgo)
3. PG 76-22 SBR modified (Random Styrene Butadiene Co-polymer)
4. PG 76-22 SBS modified (Block Styrene Butadiene Co-polymer)
5. PG 76-22 Multi-grade.

3. Penetration and NCDOT Test Results for AC-20 Crumb Rubber Modified Asphalt Binders

3.1 Penetration Test Results

Conventional penetration test was performed on the AC-20 base and crumb rubber modified binders to evaluate the effect of the crumb rubber particle size and its concentration on the conventional penetration test results. Testing was conducted at 25°C in accordance with the ASTM D5 test method [5] (Standard Test Method for Penetration of Bituminous Materials). Average of 10 penetration test results for the base and modified binders are presented in Table 3-1 and Figure 3-1.

Table 3-1 Penetration test results

Asphalt Type	Mean Penetration Value, dmm.	Standard Deviation (s)	Coefficient of Variation (CV, %)
AC-20 Base	85	1.60	1.9
AC-20 Processed	80	1.07	1.3
AC-20+7%CR	56	1.81	3.2
AC-20+7%FR	51	1.34	2.6
AC-20+14%CR	42	3.09	7.3
AC-20+14%FR	41	1.48	3.6

Test results show that in general, the mean penetration values decrease with increasing concentration of crumb rubber. In particular, the following conclusions can be noted:

1. The effect of processing the AC-20 base asphalt for 90 minutes reduced the penetration value by 5 dmm.

2. On an average, addition of 7% crumb rubber results in approximately 33% reduction in the penetration values.
3. On an average, addition of 14% crumb rubber results in approximately 48% reduction in the penetration value.
4. Addition of 14% crumb rubber results in roughly 2 level binder grade jump. That is, an essentially 85-100 pen. asphalt cement (AC-20) results in a 40-50 pen asphalt binder. As will be shown in section 5, the 2 level binder grade jump is surprisingly consistent with a 2 grade increase in PG grading of AC-20 containing 14% crumb rubber.
5. The coefficient of variation of the test results increase with increasing crumb rubber content. For the same percentages of crumb rubber, the coefficient of variations are substantially higher for the 40-mesh CR as compared with the 80-mesh FR.

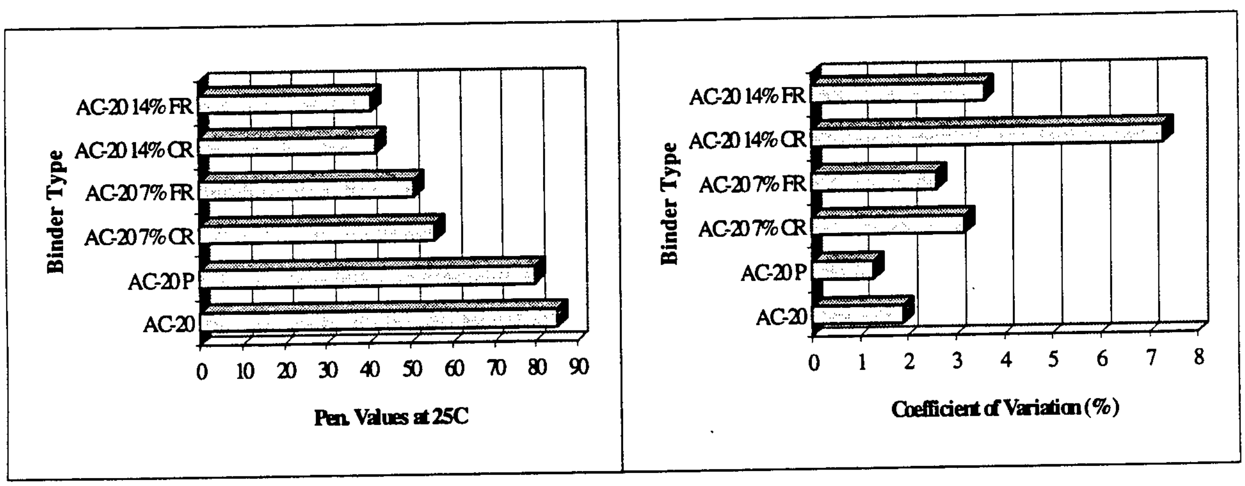

Figure 3-1 Effect of crumb rubber on penetration and coefficient of variation values

3.2 Results of Tests Conducted at NCDOT M&T Unit

3.2.1 Dynamic Shear Rheometer (DSR) Test Results

AC-20 modified with 7% coarse and fine rubber was tested using the DSR. No replication testing was done for these specimens. Each of the specimens were tested in their unaged, RTFO aged and PAV aged conditions. The testing was carried out at 58, 64, and 70° C, and confirmed to the AASHTO TP5 test protocol. The test results are tabulated in Tables 3-2, 3-3, and 3-4.

Table 3-2 Unaged AC-20 modified binders, G*/sinδ, kPa, NCDOT test results

Material	Temperature, °C		
	58	64	70
AC-20+7%Fine Rubber	5.36	2.63	1.32
AC-20+7%Coarse Rubber	6.37	3.12	1.56

Table 3-3 RTFO aged AC-20 modified binders, G*/sinδ, kPa, NCDOT test results

Material	Temperature, °C		
	58	64	70
AC-20+7%Fine Rubber	15.7	8.09	4.19
AC-20+7%Coarse Rubber	15.98	8.34	4.45

Table 3-4 PAV aged AC-20 modified binders, G*/sinδ, kPa, NCDOT test results

Material	Temperature, °C		
	25	22	19
AC-20+7% Fine Rubber	2202.60	3201.20	4269.80
AC-20+7% Coarse Rubber	2268.30	3296.60	4747.40

Based on the Superpave™ binder specifications listed in Figure 1-1 (AASHTO MP1), the modified binders in Tables 3-2 through 3-4 were high temperature performance graded PG 70-y. These test results are compared with the NCSU test results in section 5.1.2.

3.2.2 Bending Beam Rheometer (BBR) Test Results

Low temperature testing was carried out on the AC-20 asphalt modified with 7% coarse and fine rubber as per the AASHTO TP1 test protocol. The modified binders were tested at -12 °C , and -18 °C. No replicate testing was done for these specimens. The test results are tabulated in Table 3-5. Based on the test results and AASHTO MP1 specifications, both binders containing 7% coarse and fine crumb rubber were assigned a low temperature grade of -22°C.

Table 3-5 BBR Test Results

Material	Temperature °C	Stiffness MPa	m-Value
AC-20+7% Fine Rubber	-12	130.3	0.33
	-18	281.1	0.294
AC-20+7% Coarse Rubber	-12	123.5	0.337
	-18	289.4	0.29

3.2.3 Rotational Viscosity Test Results

The rotational viscosity test was performed on all types of unmodified and modified AC-20 asphalt binders, viz.: virgin AC-20, AC-20 Processed, AC-20 modified with 7% fine and coarse rubber, and AC-20 modified with 14% coarse and fine rubber. This test determines the flow characteristics of the asphalt binders. The test was performed as per the ASTM D 4402 test protocol, at 135 °C using the Brookfield Rotational Viscometer. The test results are tabulated in Table 3-6.

Table 3-6 Rotational Viscosity Test Results

Material	Temperature °C	Viscosity Pa.s
AC-20 (virgin)	135	0.468
AC-20 (processed)	135	0.480
AC-20+7% Fine Rubber	135	1.058
AC-20+7% Coarse Rubber	135	0.978
AC-20+14% Fine Rubber	135	3.550
AC-20+14% Coarse Rubber	135	3.530

The AASHTO MP1 binder specifications require that the dynamic viscosity of the binders should not exceed 3 Pa.s. The test results in Table 3-6, show that the viscosity of the AC-20 asphalt modified with 14% coarse and fine rubber exceed the specification criteria. This implies that though these binders may establish a higher PG grade they may not be satisfactory from their workability point of view.

4. Task A -- Verification of Applicability of Superpave™ Protocol to Crumb Rubber Modified Binders

The main objective of this task was to determine the effect of crumb rubber particle size and concentration in the modified binders. The tests were performed using the Superpave™ DSR test equipment and conducted as per the AASHTO TP5 protocol. This verification was conducted using only one asphalt cement (AC-20) modified with the 40-mesh (CR) and the 80-mesh (FR) crumb rubber, each with a concentration of 7 and 14%. Testing temperatures included a low, medium, and high of 12°C, 42°C and 70°C, respectively. Using the AASHTO TP5 protocol, the asphalt binders were tested at a frequency of 10 radians/second (1.59 Hz) using spindle diameters of 25 mm for the medium and high temperatures, and 8 mm for the low temperature. To decide on the thermal equilibrium time, several modified and unmodified binders were tested with a thermocouple embedded in the test specimens. Results indicated that six minutes provided adequate time for the specimen to reach thermal equilibrium. The experiment design for this task is given in section 1.2.1.

Two variables of interest were evaluated in this task:

1. Effect of crumb rubber particle size and its concentration on the measured property, $G^*/\sin\delta$, using Superpave™ test protocol (AASHTO TP5). The hypothesis was that, if the crumb rubber particles interfered with the test measurements, varying the film thickness of the binder specimen should significantly affect the measured properties. In order to validate this hypothesis, two binder film thicknesses were used. At low temperature 2 mm and 4 mm film thicknesses were evaluated. At medium and high temperatures, 1 mm and 2 mm film thickness were evaluated. It should be noted that AASHTO TP5 protocol requires film thicknesses of 2 mm and 1 mm at the low and high temperatures, respectively.
2. Effect of crumb rubber size and its concentration on the repeatability of the measured property, $G^*/\sin\delta$.

In the initial phase of this study, the following procedure was used to evaluate the effect of specimen film thickness:

1. For a given temperature, modified or unmodified binder was tested at the thickness required by the AASHTO TP5.
2. After this test was completed, the specimen was removed, the instrument was cleaned and a new specimen was setup with twice the thickness used in step 1 and tested again at the same temperature.
3. Step 1 and 2 were repeated for a different set of specimens to evaluate the repeatability of the test results.

Preliminary analysis of data obtained using the above procedure indicated that the effect of the specimen thickness and test repeatability could not be separated using the above procedure. This was due to the fact that a different specimen was used each time the specimen thickness was varied. Thus, it could not be determined whether the difference in test results was due to thickness variation or the sample variation. Therefore, the testing procedure was modified as follows:

1. For a given temperature, modified or unmodified binder was tested at twice the thickness required by AASHTO TP5. For example, at 70°C, the required specimen thickness is 1 mm. Therefore, testing was first conducted with a specimen of 2 mm thickness.
2. After the first test was completed, specimen temperature was brought back to that specified by the AASHTO TP5 procedure (45°C); specimen thickness was reduced to the new required thickness (e.g. from 2 mm to 1 mm); excess material was trimmed off and the specimen was tested at the required temperature.
3. Steps 1 and 2 were repeated for a second specimen to evaluate the repeatability in test results.

In order to differentiate between the two procedures, results for the former procedure are presented as Subtask A1 and the latter as Subtask A2. Figure 4-1 summarizes the two subtasks.

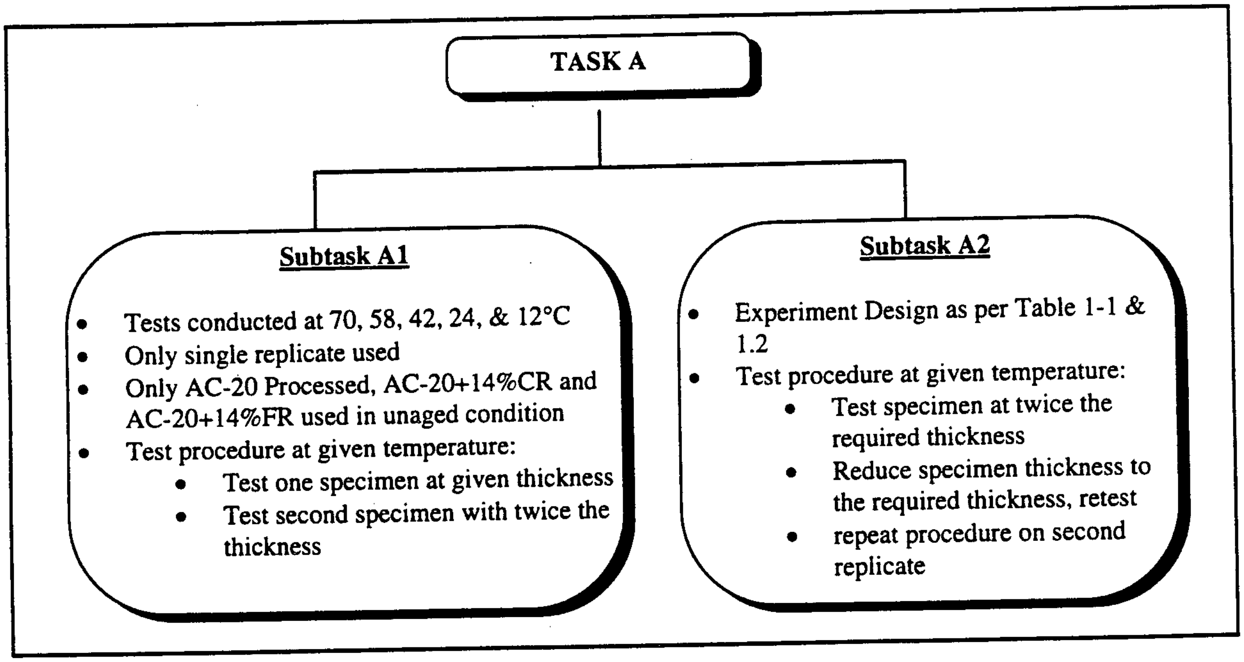

Figure 4-1 Summary of subtasks A1 and A2

4.1 Test Results for Subtask A1

Detailed test results for this subtask are presented in Appendix A1 of this report. Results for each asphalt binder include the test measurement G* (dynamic shear modulus) and δ (phase angle) at 10 radians/second, at various temperatures and strain levels. Testing at different strain levels (strain sweep) was conducted to establish for each modified and unmodified binder, the linear viscoelastic region in the strain domain (defined by AASHTO TP5 to be a range of strain values where the test measurement G* does not vary more than 95% of the G* estimated at zero strain). Test results presented in Appendix A1 indicated that at higher temperatures, test measurements were in the linear viscoelastic range for measurements taken within 10% strain level. For this reason, summary of the average results presented in Table 4-1 represent averages over a range in strain level up to 10%. At lower temperature due to the limitation of the instrument, strain levels more than 3 to 4 percent were not achieved. Therefore, the average of all the results were taken.

Table 4-1 Test results for unaged asphalt binders -- average G*/sinδ, subtask A1

Binder Type	Temp. °C	Specimen No.	Specimen Thickness, mm	G*/sinδ kPa	% Absolute Difference
AC-20 Processed	70	1	1	0.626	
		2	2	1.470	57.4
AC-20+14%CR	70	1	1	4.203	
		2	2	3.500	16.7
AC-20+14%FR	70	1	1	4.226	
		2	2	3.720	12.0
				Average	**28.7**
AC-20 Processed	58	1	1	2.670	
		2	2	2.680	0.4
AC-20+14%CR	58	1	1	12.80	
		2	2	13.80	7.2
AC-20+14%FR	58	1	1	13.50	
		2	2	13.40	0.7
				Average	**2.8**
AC-20 Processed	42	1	1	22.90	
		2	2	20.70	10.6
AC-20+14%CR	42	1	1	68.40	
		2	2	62.30	9.8
AC-20+14%FR	42	1	1	82.30	
		2	2	74.00	11.2
				Average	**10.5**
AC-20 Processed	24	1	1	557.30	
		2	2	746.00	25.3
AC-20+14%CR	24	1	1	---	---
		2	2	---	---
AC-20+14%FR	24	1	1	966.00	
		2	2	938.00	2.9
				Average	**14.1**

Table 4-1 shows the effect of variation in specimen thickness on the shear stiffness value, G*/sinδ. For the limited test results presented in this table, the average percentage difference due to variation in thickness ranged from a low of 2.8 percent to a high of 28.7 percent with an overall average of approximately 14 percent. It should be noted that at 24°C and 70°C, the percentage difference in G*/sinδ for AC-20 Processed asphalt is more than those binders which contain 14 percent coarse and fine crumb rubber. For other temperatures, the percentage difference for modified binders is equal to or lower than the unmodified AC-20 Processed asphalt cement. It should be specifically noted that the average 14 percent difference in test measurements is inclusive of both the variables -- variation in binder film thickness and the use of dual specimens for the two thicknesses evaluated. Also, any operator related sample setup effect is also inherent in the difference. The significance of these results will be further discussed in the following section.

4.2 Test Results for Subtask A2

Unaged AC-20 processed and crumb rubber modified binders were tested in this subtask according to the experiment design outlined in Table 1-2. In addition, AC-20 binder containing 14% CR and 14% FR was evaluated in RTFO and PAV aged conditions. Detailed test results are presented in Appendix A2 of this report. Results for each asphalt binder include the test measurement G* (dynamic shear modulus) and δ (phase angle) at 10 radians/second, at various temperatures and strain levels identified in the experiment design. Similar to subtask A1, testing at different strain levels (strain sweep) was conducted to establish the linear viscoelastic region in the strain domain for each modified and unmodified binder. Summary of the average results presented in Tables 4-2 through 4-4 represent averages based on tests conducted at 2, 5, and 10 percent strain. It should be noted that at 12°C higher strain levels could not be achieved due to the torque limitations of DSR.

Due to the nature of this experiment, it was possible to evaluate separately the effect of asphalt film thickness and test repeatability from the test results obtained. Tables 4-2 through 4-4 present the average test measurement G*/sinδ for replicate specimens as a function of temperature and specimen thickness for each binder type. Based on these average values, percentage differences (absolute values) were computed for the two film thicknesses and for the repeat testing.

4.2.1 Effect of Binder Film Thickness

Tables 4-2 though 4-4 indicate that the percentage difference in the measured values due to difference in specimen thickness varies between 0.5 to 21 percent (except in one or two instances where it exceeds this range). For the unaged binders, there seems to be a general trend of increased percentage difference with increase in crumb rubber modifier concentration. This difference varies between 6.4% for the AC-20 processed binder to 10% for the AC-20+14%FR. With regards to the crumb rubber particle size, the percentage differences for the coarse rubber modified binder is lower than for the fine rubber modified binder. This is also true for the RTFO aged binders. For the PAV aged binders, the percentage difference due to specimen thickness is similar for binders containing coarse and fine rubber. The overall averages for the unaged, RTFO aged and PAV aged binders are 7.7, 8.5, and 11%, receptively. However, it should be noted that the averages for the RTFO and PAV aged binders are based on limited testing of AC-20 containing 14% crumb rubber only, as compared to testing of unaged binders. The average effect of specimen film thickness on the $G^*/\sin\delta$ values for the unaged binders are shown in Figures 4-2 through 4-5.

4.2.2 Effect of Replicate Specimens

For the test repeatability, the percentage difference between two replicate specimens presented in Tables 4-2 through 4-4 do not indicate any consistent trends. Percentage difference for the unmodified AC-20 processed asphalt is in many instances equal to or higher than those observed for the modified binders. With regards to the crumb rubber particle size, in general, the percentage difference is higher for the binder containing the coarser particles for both 7 and 14% concentrations. This observation is not in agreement with the effect of the specimen film thickness where the binders containing the finer particles showed a higher percentage difference. If the coarser rubber particles were to affect the test measurements, it is reasonable to assume that particle size would have similar effect on both the measurements -- specimen thickness and repeatability. The overall percentage difference for the unaged, RTFO aged, and PAV aged binders are 7.6, 9.7, and 9%, respectively.

4.2.3 Coefficient of Variation

Coefficient of variation (CV) values indicate inherent variation in the measured parameters due to differences in specimen film thickness and due to replicate testing. The CV values were computed using the following relationship:

$$\mathbf{CV = 100\,(e^{Var} - 1)^{0.5}} \tag{4.1}$$

where,
CV = coefficient of variation;
Var. (s^2) = variance due to sample thickness or replicate testing for the natural log transformed data;
e = base of natural logarithm.

The variance (s^2) was estimated using the following relationship:

$$s^2 = \frac{\left(\sum \frac{1}{2}\left[\mathrm{Ln}\left(N_1/N_2\right)\right]^2\right)}{(\#\mathrm{Obs})} \tag{4.2}$$

where:
s^2 = sample variance due to differences in thickness or replicate testing;
N_1 = measured value at 2 mm (or 4 mm) thickness or replicate 1;
N_2 = measured value at 1 mm (or 2 mm) thickness or replicate 2; and
Obs = number of replicate pairs.

Table 4-2 Test results for unaged asphalt binders -- average G*/sinδ, subtask A2

Binder Type	Temp. °C	Specimen No.	Specimen Thickness, mm.	G*/sinδ kPa	% Abs. Diff. Due to Thickness	% Abs. Diff. Due to Replicate
AC-20 Processed	70	1	2	0.678		
			1	0.611	9.9	5.9
		2	2	0.718		
			1	0.771	7.4	26.1
AC-20 Processed	42	1	2	30.36		
			1	29.27	3.6	2.9
		2	2	29.48		
			1	29.56	0.3	1.0
AC-20 Processed	12	1	4	5860		
			2	6530	11.4	10.2
		2	4	6460		
			2	6830	5.7	4.6
				Average	**6.4**	**8.5**
AC-20+7% CR	70	1	2	1.650		
			1	1.727	4.5	7.3
		2	2	1.530		
			1	1.340	12.4	22.4
AC-20+7% CR	42	1	2	64.19		
			1	50.76	20.9	2.2
		2	2	62.78		
			1	60.90	3.0	16.7
AC-20+7% CR	12	1	4	5860		
			2	5740	2.0	3.1
		2	4	6040		
			2	5840	3.3	1.7
				Average	**7.7**	**8.9**
AC-20+7% FR	70	1	2	1.522		
			1	1.480	2.8	9.5
		2	2	1.377		
			1	1.382	0.4	6.6
AC-20+7% FR	42	1	2	55.20		
			1	46.37	16.0	4.5
		2	2	52.73		
			1	47.17	10.5	1.7
AC-20+7% FR	12	1	4	6240		
			2	6670	6.9	3.4
		2	4	6030		
			2	7000	16.1	4.9
				Average	**8.8**	**5.1**

Table 4-2 (continued)

Binder Type	Temp. °C	Specimen No.	Specimen Thickness, mm.	G*/sinδ kPa	% Abs. Diff. Due to Thickness	% Abs. Diff. Due to Replicate
AC-20+14% CR	70	1	2	4.020		
			1	4.123	2.5	0.7
		2	2	3.993		
			1	4.290	6.9	3.9
AC-20+14% CR	42	1	2	81.09		
			1	79.25	2.3	7.9
		2	2	87.52		
			1	95.53	8.4	17.0
AC-20+14% CR	12	1	4	7760		
			2	7220	7.0	12.0
		2	4	8690		
			2	8160	6.1	13.0
				Average	**5.5**	**9.1**
AC-20+14% FR	70	1	2	4.049		
			1	3.270	19.2	15.0
		2	2	3.443		
			1	3.747	8.1	12.7
AC-20+14% FR	42	1	2	95.30		
			1	80.53	15.5	0.3
		2	2	95.59		
			1	81.32	14.9	1.0
AC-20+14% FR	12	1	4	9270		
			2	9010	2.8	6.0
		2	4	8710		
			2	8590	1.4	4.7
				Average	**10.3**	**6.6**

Table 4-3 Test results for RTFO aged asphalt binders -- average G*/sinδ, subtask A2

Binder Type	Temp. °C	Specimen No.	Specimen Thickness, mm.	G*/sinδ kPa	% Abs. Diff. Due to Thickness	% Abs. Diff. Due to Replicate
AC-20+14% CR	70	1	2	11.10		
			1	11.70	5.4	6.3
		2	2	10.40		
			1	10.52	1.2	10.1
AC-20+14% CR	42	1	2	145.0		
			1	141.0	2.8	3.4
		2	2	140.0		
			1	133.0	5.0	5.7
AC-20+14% CR	12	1	4	4620		
			2	4240	8.2	2.2
		2	4	4720		
			2	4800	1.7	13.2
				Average	**4.0**	**6.8**
AC-20+14% FR	70	1	2	7.743		
			1	7.630	1.5	3.0
		2	2	7.510		
			1	7.213	4.0	5.5
AC-20+14% FR	42	1	2	140.1		
			1	141.3	0.9	2.6
		2	2	143.7		
			1	128.9	10.3	8.8
AC-20+14% FR	12	1	4	4633		
			2	2790	39.8	13.0
		2	4	4030		
			2	4870	20.8	42.7
				Average	**12.9**	**12.6**

Table 4-4 Test results for PAV aged asphalt binders -- average G*/sinδ, subtask A2

Binder Type	Temp. °C	Specimen No.	Specimen Thickness, mm.	G*/sinδ kPa	% Abs. Diff. Due to Thickness	% Abs. Diff. Due to Replicate
AC-20+14% CR	70	1	2	24.60		
			1	24.20	1.6	2.4
		2	2	25.20		
			1	28.10	11.5	16.1
AC-20+14% CR	42	1	2	305.0		
			1	290.0	4.9	2.6
		2	2	297.0		
			1	259.0	12.8	10.7
AC-20+14% CR	12	1	4	19300		
			2	22200	15.0	6.2
		2	4	20500		
			2	16000	22.0	27.9
				Average	**11.3**	**11.0**
AC-20+14% FR	70	1	2	6.09		
			1	6.68	9.7	0.7
		2	2	6.05		
			1	6.54	8.1	2.1
AC-20+14% FR	42	1	2	203.0		
			1	241.0	18.7	23.6
		2	2	251.0		
			1	225.0	10.4	6.6
AC-20+14% FR	12	1	4	21100		
			2	22000	4.3	6.6
		2	4	19700		
			2	22200	12.7	0.9
				Average	**10.6**	**6.8**

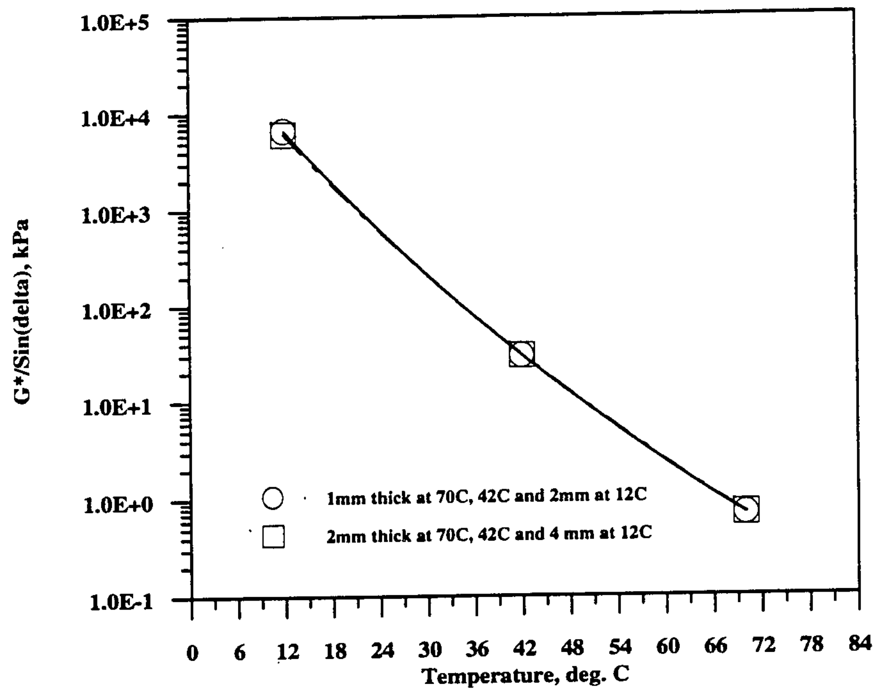

Figure 4-2 Effect of specimen film thickness on G*/sinδ values, unaged AC-20 processed

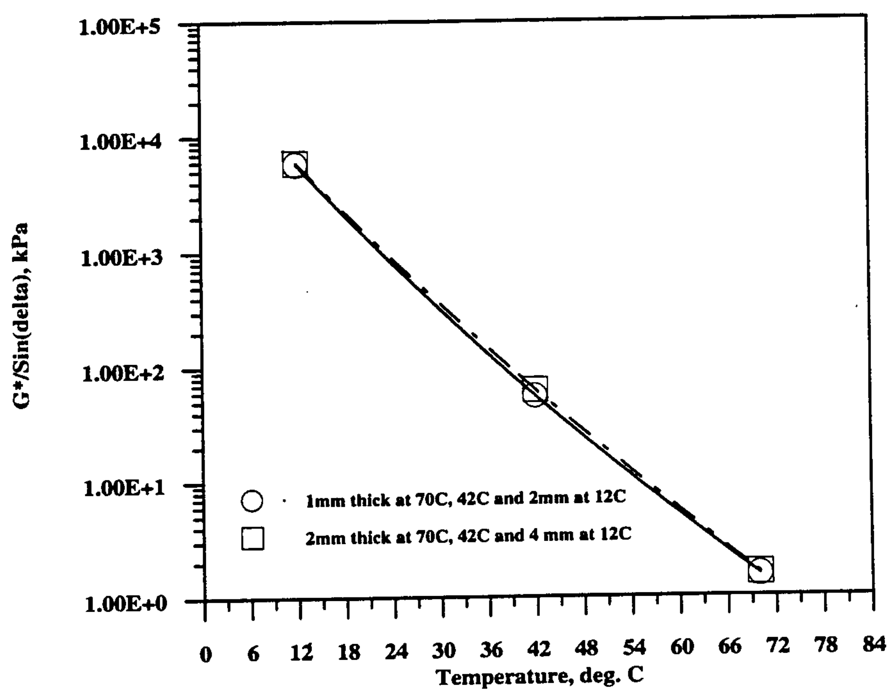

Figure 4-3 Effect of specimen film thickness on G*/sinδ values, unaged AC-20+7% CR

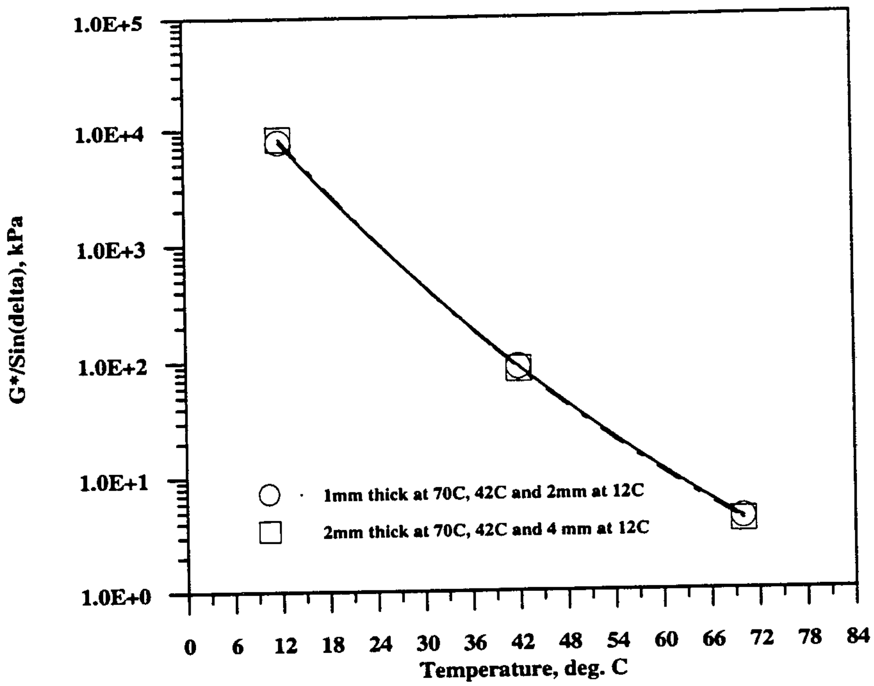

Figure 4-4 Effect of specimen film thickness on G*/sinδ values, unaged AC-20+14% CR

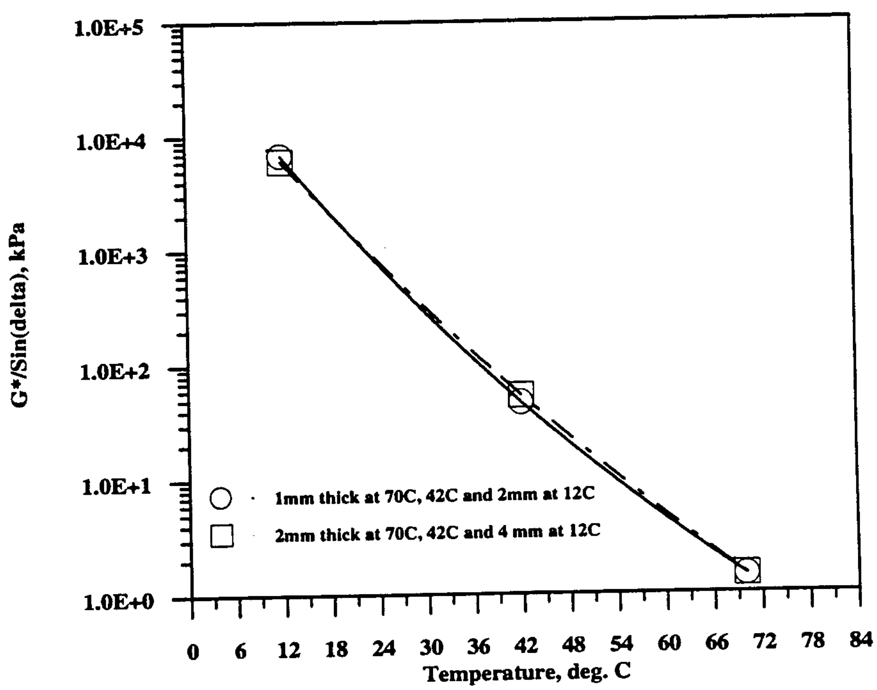

Figure 4-5 Effect of specimen film thickness on G*/sinδ values, unaged AC-20+7% FR

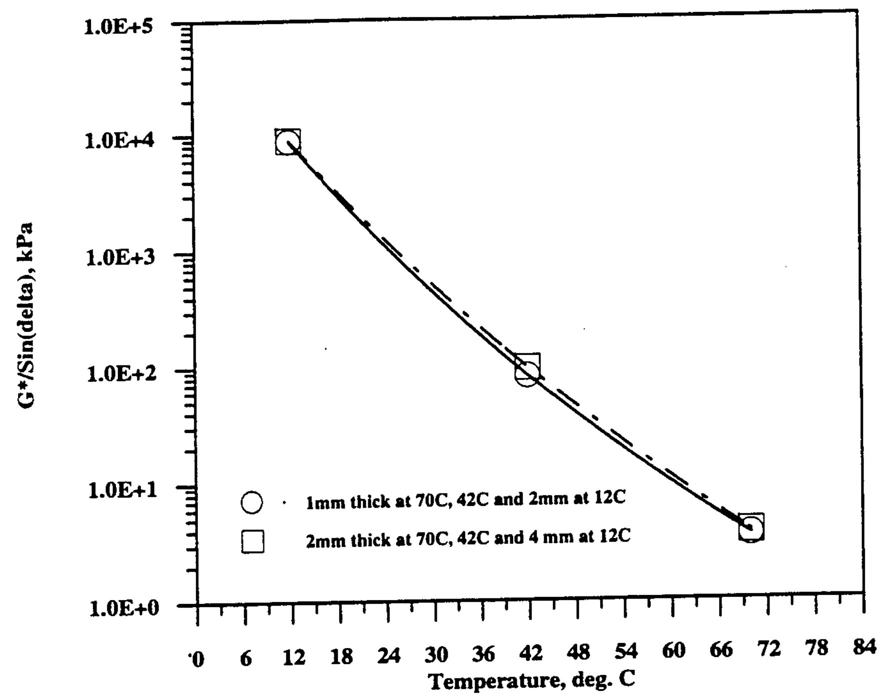

Figure 4-6 Effect of specimen film thickness on G*/sinδ values, unaged AC-20+14% FR

Table 4-5 summarizes both the percent difference and the CV values computed using equations 1 and 2. Results indicate that there is a small increase in CV for the modified binders compared to unmodified binder. However, there is no consistent trend with regards to either, the crumb rubber particle size or concentration. The aging process does seem to introduce larger variability, however, limited test results for RTFO and PAV aged samples may explain the higher CV values. It is of particular interest to note that the overall CV values due to the differences in specimen film thickness and replicate testing are similar, 6.2% and 6.5% respectively.

4.3 Statistical Analysis of Test Results

To determine the statistical significance of the use of different thicknesses of test specimens and to evaluate the effect of repeatability, an F-test was performed on the test data. An F-test which is an analysis of variance procedure, essentially gives an indication whether the parameter being evaluated has any significant effect on the measured values. An F-value is the ratio of variance in sample means to the mean of sample variances. This can be expressed as follows:

Table 4-5 Average coefficient of variation and percent difference for binder types

Aging	Binder Type	Coefficient of Variation, %		% Absolute Difference due to	
		Specimen Thickness	Replicate Specimen	Specimen Thickness	Replicate Specimen
Unaged	AC-20 Processed	3.7	5.4	6.4	8.5
	AC-20+7%CR	5.7	6.6	7.7	8.9
	AC-20+7%FR	5.4	2.9	8.8	5.1
	AC-20+14%CR	3.1	5.4	5.5	9.1
	AC-20+14%FR	6.7	4.6	10.3	6.6
Average		5.1	5.2	7.7	7.6
RTFO Aged	AC-20+14%CR	2.4	3.9	4.0	6.8
	AC-20+14%FR	11.3	12.0	12.9	12.6
Average		8.2	8.9	8.5	9.7
PAV Aged	AC-20+14%CR	6.9	7.8	11.3	11.0
	AC-20+14%FR	5.5	4.8	10.6	6.8
Average		6.3	6.5	11.0	9.0
Overall Average		**6.2**	**6.5**	**8.6**	**8.4**

$$F = \frac{n(\text{variance of sample means})}{\text{mean of sample variances}} \tag{4-3}$$

For the data obtained in this study the F-test was conducted using the following hypothesis:

Hypothesis: 1. The 2 mm specimen thickness does not affect the values of measured variable as compared to the 1 mm specimen thickness used.

2. The crumb rubber particles do not affect the test results when the specimens are tested in replication.

Significance Level and Critical Region: For a significance level of 0.05 and corresponding to degree of freedom one for the numerator and 106 for the denominator, the F-table , from any standard statistical book, indicates 3.94 to be the significant value.

Computation of Statistics: The analysis was conducted using the Microsoft Excel Statistical Package. F-values of 0.856 and 0.705 were obtained as shown in Table 4.6 for the two hypothesis being tested.

Decision: Based on the F-test results, it can be conclude that the variables being evaluated do not affect the test results. This indicates that the different specimen thicknesses used and replication of specimens do not significantly affect the test results.

Table 4-6 Test results from F-statistics

Variable	Computed F-value	Significant Value @ 95% confidence level	Statistically Significant
Specimen Thickness	0.856	3.94	NO
Replication	0.705	3.94	NO

4.4 Conclusion

The objective of the verification study was to evaluate the effect of rubber particle size and concentration on the measured stiffness values. The basic hypothesis was that if the rubber particle size and concentration did indeed affect the stiffness, a variation would result from testing specimens with different film thickness. An average coefficient of variation of 6.2% was obtained based on the results of this study.

Replicate testing enabled evaluation of sample to sample variance. The coefficient of variation obtained due to replication was 6.5%, practically the same value as that obtained for the specimen film thickness. If these two values were different, it would be justified to conclude that one or the other factor being investigated did have an effect on the measured property. However, because both the CV values are nearly the same, it may be inferred that the differences are primarily associated to the ***sample variance itself and the specimen setup process (operator related), and not because of the interference due to crumb rubber particles***. Also, this argument can be substantiated by the fact that results of Tables 4-2 through 4-4 show that the thicker specimens give a higher $G^*/\sin\delta$ values compared to thinner specimens in some cases, but in other cases the trend is reversed. At the same time, the CV value of approximately 6.5% compares quite well with the 9.2% obtained for the results of subtask A1. It should be recalled that in subtask A1 due to the nature of the experiment design, this CV value represents the combined effect of the specimen thickness as well as the effect of sample to sample variation.

The validity of these conclusions is substantiated by the statistical tests conducted on the test data. From the results tabulated in Table 4-6, it was observed that the specimen thickness and the replication of specimens, statistically did not affect the measured test results.

Although, it is indeed true that modification of AC-20 slightly increased the coefficient of variation, the increase in CV values are small. It can therefore be concluded, that the AASHTO TP5 test protocol is applicable for the crumb rubber modified binders used in this study.

It should also be noted that due to the particular nature of this study, which deviates from the AASHTO standard testing procedure (since there are no molds for the thicker specimen film thickness) it is possible that a coefficient of variation lower than 6.22% may be obtained if the AASHTO procedure is used. However, a 6.5% CV value is considered a good control for the laboratory test results on stiffness considering that AASHTO TP5 procedure will inherently have some variability (apart from any random variability) due to the fact that it allows a range of test strain (or stress) values for the evaluation of binder properties in the linear viscoelastic region. This error can be as much as 5 percent based on the current protocol.

4.5 Summary and Recommendations

The main objective of Task A was to verify the applicability of the Superpave™ test protocol to crumb rubber modified binders. Results of this task indicate that the current AASHTO TP5 protocol seems to be applicable to the 40-mesh and 80-mesh crumb rubber modifier with 7 and 14 percent concentration used in this study. From the experience obtained from this task it is the opinion of the authors that much of the variation in test results could be minimized by the following:

1. It was observed during the duration of this study that the coefficient of variation was systematically reduced as the DSR operator gained more training and experience in setting up specimens, especially for the 8 mm diameter specimens.

2. Variability seemed to decrease with the use of silicon molds supplied by the Asphalt Institute for preparation of the test specimens.
3. During the time testing was conducted for this subtask the 8 mm specimens were tested using an 8 mm spindle and a DSR base plate which had a 25 mm pedestal. In this case extreme care had to be exercised to prepare the specimen properly. During testing for the task B of this project, a base plate with pedestal diameter of 8 mm was available from the DSR manufacturer. This facilitated the ease with which 8 mm specimens could be setup.
4. AASHTO TP5 suggest a range of strain (or stress) levels which may be used for testing. Test results indicate that at any temperature, a sufficiently high strain level (in the linear viscoelastic limit defined by the protocol) must be used in order to get repeatable results. On the other hand, some modified PAV aged binders at low temperatures could not be tested at acceptable strain levels (due to DSR torque limitation) to get any meaningful results.

5. Task B -- Binder Characterization using Dynamic Shear Frequency Sweep

The main objective of this task was to characterize the asphalt binders over a range of frequencies and temperatures. The tests were performed using the DSR Research Package [6]. From Task A, it was concluded that the crumb rubber particles did not interfere with the DSR test measurements. Based on this conclusion, the tests in Task B were performed in accordance with the Superpave™ AASHTO TP5 test protocol. The tests were conducted on asphalt cements AC-20 and AC-10 modified with 7% and 14% 40-mesh (CR) and 80-mesh (FR) crumb rubber, and 5 PG graded binders.

The specimens were tested at temperatures of 6, 12, 24, 30, 42, 52, 58, 64, 70, and 76 °C and frequencies of 0.1, 0.15, 0.2, 0.5, 1, 2, 5, 10, 15, and 20 Hz. A different strain levels was used for the low, medium and high temperature ranges. To determine these strain levels preliminary testing was done to establish the linear strain range of the modified binders at different temperatures. From these test results an 8% strain was selected for higher temperatures (64, 70, 76°C) testing; and 2% strain for all the other temperatures (6, 12, 24, 30, 42, 52, 58°C). The experiment design for this task is given in section 1.2.1. It should be noted that for low temperature testing a base plate with an 8 mm pedestal diameter was used (in Task A the base plate had a 25 mm pedestal).

5.1 Test Results for Task B

Similar to Task A, the test measurements of interest investigated in this task were G* and δ at different temperatures and frequencies. Test results for this task are presented in the form of regression equations in Appendix B1 of this report. Results for each asphalt binder include the test measurement G*/sin δ over a range of frequencies and testing temperatures. As mentioned before, the testing was carried out at fixed strain levels for different temperature ranges. At low temperatures (6°C and 12°C) it was observed that a 2% strain was not attainable for the modified binders due to the DSR limitation. The values of G*/sin δ corresponding to those temperatures at which the specified strain levels were not achieved have not been included in the development of the dynamic frequency curves. It was also observed that at lower frequencies (0.1 to 0.2 Hz) some of the test results showed a larger discrepancy in the replicate samples. The corresponding $G^*/\sin\delta$ values in these cases were not included in developing the frequency sweep curves.

5.1.1 Coefficient of Variation

The coefficient of variation (CV) values were computed as explained in section 4.2.3 for comparison with those obtained for Task A. The CV values indicate the variation in the measured parameters due to replicate testing. Table 5-1 summarizes the CV values computed for all the asphalt binders tested in their unaged and RTFO aged conditions. The CV values for the base asphalt binders modified with 80 mesh crumb rubber (FR) in general, tend to show higher CV values as compared to the other modified binders. The PG graded binders also show high CV values but do not exhibit any particular trend. In general, the RTFO aging process doesn't seem to affect the CV values.

An overall average CV value of 13.8% was obtained for this task which is much higher than the 6.5% obtained for Task A. It should be noted that this value is inclusive of test measurements at all temperatures using the DSR research package, rather than the Superpave™ binder specification package used in Task A. Test results indicate that most of the high variability can be attributed to testing at 6°C and 12°C. Based on the results of this investigation, the DSR research package may not be suitable for precision low temperature testing.

5.1.2 Performance Grading of Unmodified and Modified Binders

For the intermediate and high temperatures, AASHTO MP1 (Standard Specification for Performance Graded Asphalt Binder) performance grading specification (Figure 1-1) requires binders to be tested in unaged and RTFO aged condition. For this reason, test results in the following section presents test measurements for unaged and RTFO aged binders only.

Table 5-1 Average coefficient of variation for unmodified and modified binders

Aging	Binder Type	Coefficient of Variation % Replicate Specimen	Aging	Binder Type	Coefficient of Variation % Replicate Specimen	Aging	Binder Type	Coefficient of Variation % Replicate Specimen
Unaged	AC-20 Processed	3.92	Unaged	AC-10 Processed	5.92	Unaged	PG 64-y	2.81
	AC-20 +7% CR	6.84		AC-10 + 7% CR	6.62		PG 70-y	--
	AC-20 + 14% CR	13.32		AC-10 + 14% CR	27.47		PG 76-y	4.85
	AC-20 +7% FR	26.97		AC-10 + 7% FR	12.89		PG 76-y SBS	16.28
	AC-20 +14% FR	3.59		AC-10 +14% FR	4.72		PG 76-y SBR	4.83
Average		14.83	Average		15.34	Average		9.84
RTFO	AC-20 Processed	3.67	RTFO	AC-10 Processed	9.89	RTFO	PG 64-y	24.95
	AC-20 +7% CR	5.04		AC-10 + 7% CR	8.03		PG 70-y	--
	AC-20 + 14% CR	9.50		AC-10 + 14% CR	6.56		PG 76-y	9.36
	AC-20 +7% FR	26.54		AC-10 + 7% FR	2.60		PG 76-y SBS	4.20
	AC-20 +14% FR	21.02		AC-10 +14% FR	16.28		PG 76-y SBR	6.57
Average		16.44	Average		9.78	Average		14.88
Overall Average		15.70	Overall Average		12.68	Overall Average		12.55

Overall Average = 13.84

No Bending Beam Rheometer testing was conducted in this study to evaluate the low temperature performance grading of the crumb rubber modified binders except for the limited testing conducted by NCDOT M&T unit (Section 3.2.2) on the AC-20+7% FR and CR.

Based on the measured $G^*/\sin\delta$ values over a range of frequencies at each temperature, dynamic shear frequency curves were developed. The value of $G^*/\sin\delta$ at 10 radians per second (1.59 Hz) was determined from the regression fit of the frequency curves which were of the form:

$$\mathbf{G^*/\sin\delta = a\ (frequency)^{b}} \tag{5.1}$$

The values for the regression constants a and b are included in Appendix B1. The average values of $G^*/\sin\delta$ determined using these regression equations are included in Appendix B2 for all the 15 asphalt binders tested.

The relationship between G*, the phase angle and frequency was also determined using the regression fit of the form:

$$\mathbf{LnG^* = a + b^*Ln(Temp) + c^*Ln(Freq) + d^*Ln(Temp)^*Ln(Freq) + e^*\{Ln(Temp)\}^2 + f^*\{Ln(Freq)\}^2} \tag{5.2}$$

$$\mathbf{Ln(Phase) = a + b^*Ln(G^*) + c^*Ln(G^*)^2 + d^*Ln(G^*)^3} \tag{5.3}$$

The values for the regression constants in the above equations 5.2, and 5.3 are included in Appendix B3. These test results are compared with those performed at the NCDOT M&T laboratory in Tables 5-2 through 5-4 below. The NCSU PAV aged samples were tested at temperatures different than those of NCDOT, therefore no direct comparison could be made between those test results. Comparison of the unaged and RTFO aged samples show that the difference in results for the fine rubber modified binders is higher as compared to the coarse rubber modified binders. The overall average percentage difference between the NCDOT and NCSU test results is 11.00%. It should be noted here that no replicate testing was done on the samples tested at the NCDOT M&T Unit, which may be reflected in these high differences.

Table 5-2 Comparison of NCDOT and NCSU DSR test results, unaged binder, G*/sinδ, kPa

Temperature °C	AC-20 + 7% Fine Rubber			AC-20 + 7% Coarse Rubber		
	NCDOT	NCSU	% Difference	NCDOT	NCSU	% Difference
58	5.36	6.43	16.59	6.37	6.59	3.29
64	2.63	3.03	13.24	3.12	3.03	3.12
70	1.32	1.60	17.74	1.56	1.51	3.45

Table 5-3 Comparison of NCDOT and NCSU DSR test results, RTFO aged binder, G*/sinδ, kPa

Temperature °C	AC-20 + 7% Fine Rubber			AC-20 + 7% Coarse Rubber		
	NCDOT	NCSU	% Difference	NCDOT	NCSU	% Difference
58	15.7	13.72	14.47	15.98	15.6	2.43
64	8.09	6.84	18.30	8.34	7.70	8.29
70	4.19	3.40	23.31	4.45	4.13	7.79

Table 5-4 Comparison of NCDOT and NCSU DSR test results, PAV aged binder, G*sinδ, kPa

Temperature °C	AC-20 + 7% Fine Rubber			AC-20 + 7% Coarse Rubber		
	NCDOT	NCSU @24° C	% Difference	NCDOT	NCSU @24° C	% Difference
25	2202.6			2268.3		
22	3201.2	2553.68	--	3296.6	2577.83	--
19	4269.8			4747.4		

Relationships between average values of G*/sinδ at 10 radians per second and test temperature are presented in Figures 5-1 through 5-6. For the high temperature performance grading, AASHTO MP1 specification requires that minimum value for G*/sinδ be equal to or more than 1.0 kPa and 2.2 kPa for the unaged and RTFO aged binders, respectively. Table 5-5 shows the high temperature PG grading of the base and modified binders evaluated using Figures 5-1 through 5-6 and the AASHTO MP1 limiting stiffness specification values.

Based on the results of Table 5-5, the following can be concluded:

1. The base asphalts AC-20 and AC-10 are PG 64-y and PG 58-y, respectively.
2. For both AC-20 and AC-10 asphalts, addition of 7% crumb rubber produces a one grade jump; i.e., from PG 64-y and PG 58-y to PG 70-y and PG 64-y, respectively.
3. The NCDOT test results show that the low temperature grading for the AC-20 asphalt modified with 7% coarse and fine rubber was -22 °C. Therefore, AC-20 modified with 7% crumb rubber can be assigned a grade of PG 70-22.
4. For 7% concentration, the crumb rubber particle size does not appear to have any effect on the performance grading of both the base modified asphalt cements.
5. For AC-20 asphalt cement, addition of 14% crumb rubber produces a two grade jump; i.e., from PG 64-y to PG 76-y for both the binders containing coarse and fine rubber particles. Results in Table 3-6 show that the rotational viscosity of these modified binders exceed those specified by AASHTO MP1 specification. This indicates that AC-20 asphalt modified with 14% crumb rubber is not suitable for use from the workability point of view.
6. For AC-10 asphalt cement, addition of 14% coarse rubber produces a three grade jump; i.e., from PG 58-y to PG 76-y, whereas the addition of 14% fine rubber produces a two grade jump from PG 58-y to PG 70-y.
7. For AC-10 asphalt cement, the crumb rubber particle size has an effect on the performance grading of the modified binders. This effect was not observed for AC-20 asphalt cement.
8. Except for one binder, the high temperature performance grading of the PG binders were confirmed. The PG 70-22 binder failed to achieve the 1 kPa value for the $G^*/\sin\delta$, although it did barely meet the 2.2 kPa value after RTFO aging. For this reason a grade of PG 64-y is assigned to this binder in Table 5-5.

Table 5-5 Performance grade of unmodified and modified binders

Binder Type	PG Grade
AC-20 Processed	PG 64-y
AC-20+7% CR	PG 70-y
AC-20+7% FR	PG 70-y
AC-20+14% CR	PG 76-y
AC-20+14% FR	PG 76-y
AC-10 Processed	PG 58-y
AC-10+7% CR	PG 64-y
AC-10+7% FR	PG 64-y
AC-10+14% CR	PG 76-y
AC-10+14% FR	PG 70-y
PG 64-22	PG 64-y
PG 70-22	PG 64-y (failed spec. limit of 1 kPa at 70°C)
PG 76-22 SBS modified	PG 76-y SBS
PG 76-22 SBR modified	PG 76-y SBR
PG 76-22 Multi-grade	PG 76-y Multi-grade

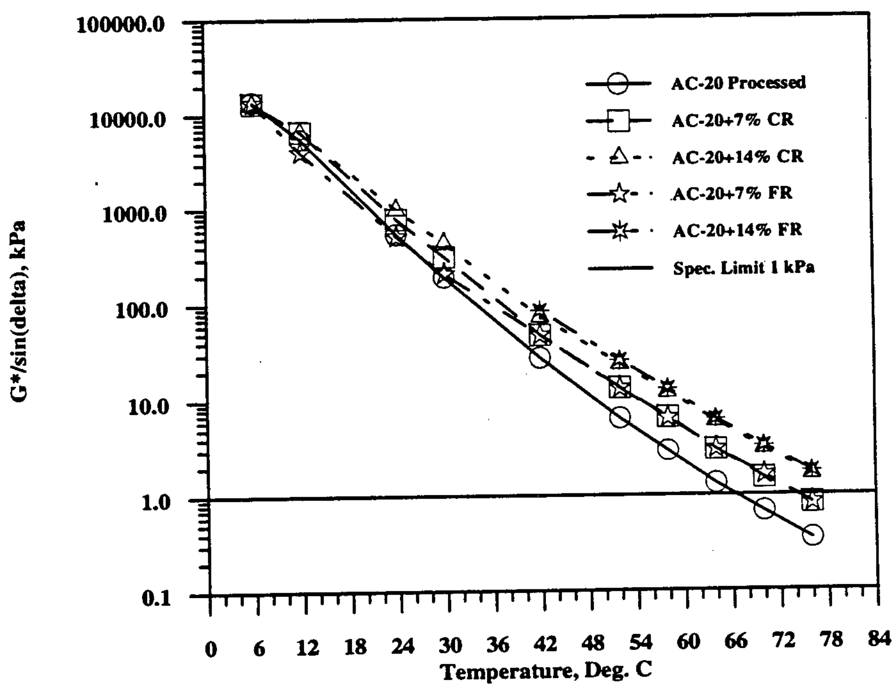

Figure 5-1 G*/sinδ versus temperature for unaged AC-20 and modified binders

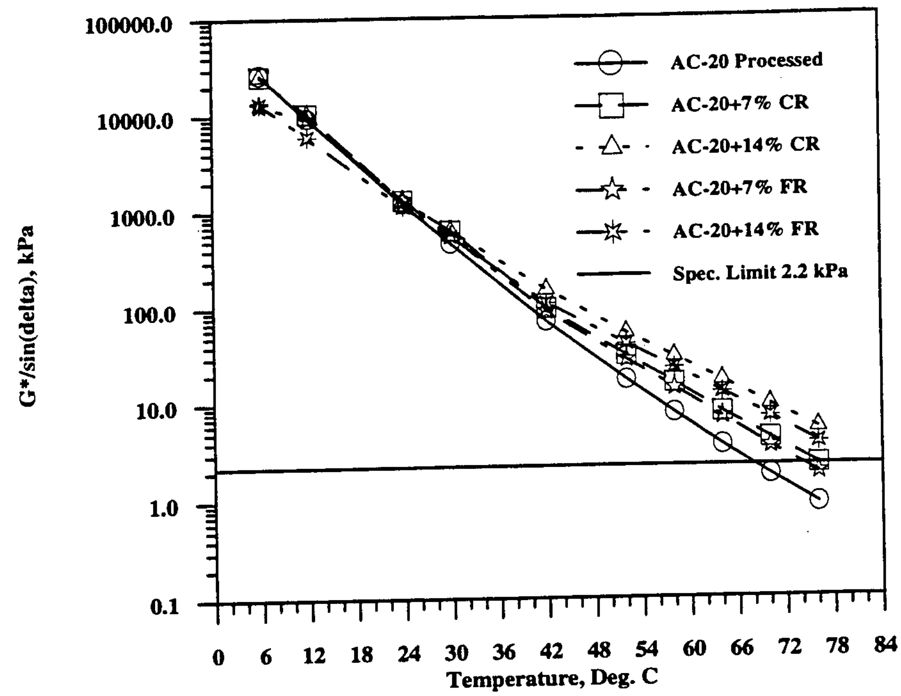

Figure 5-2 G*/sinδ versus temperature for RTFO aged AC-20 and modified binders

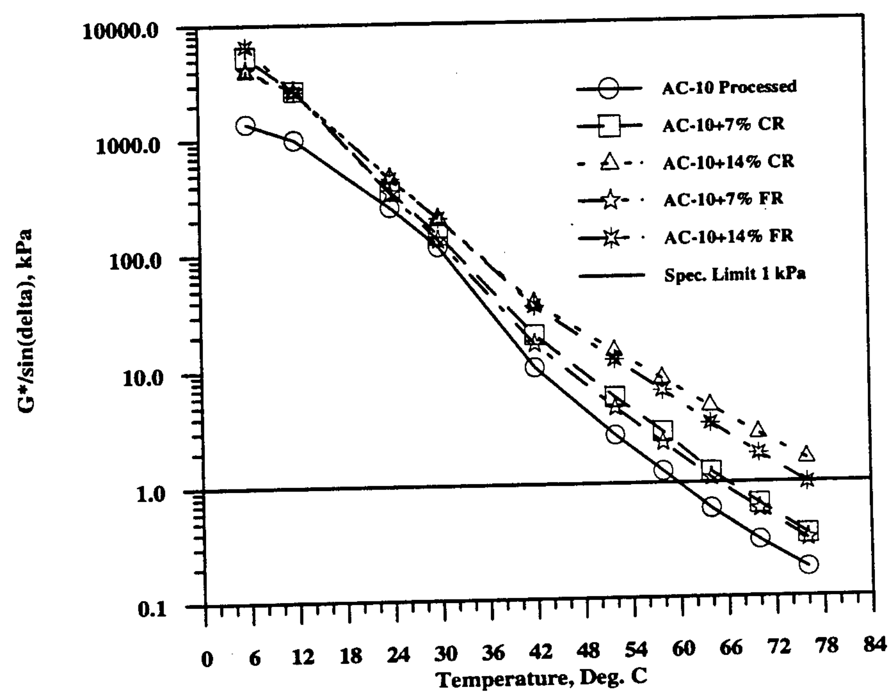

Figure 5-3 G*/sinδ versus temperature for unaged AC-10 and modified binders

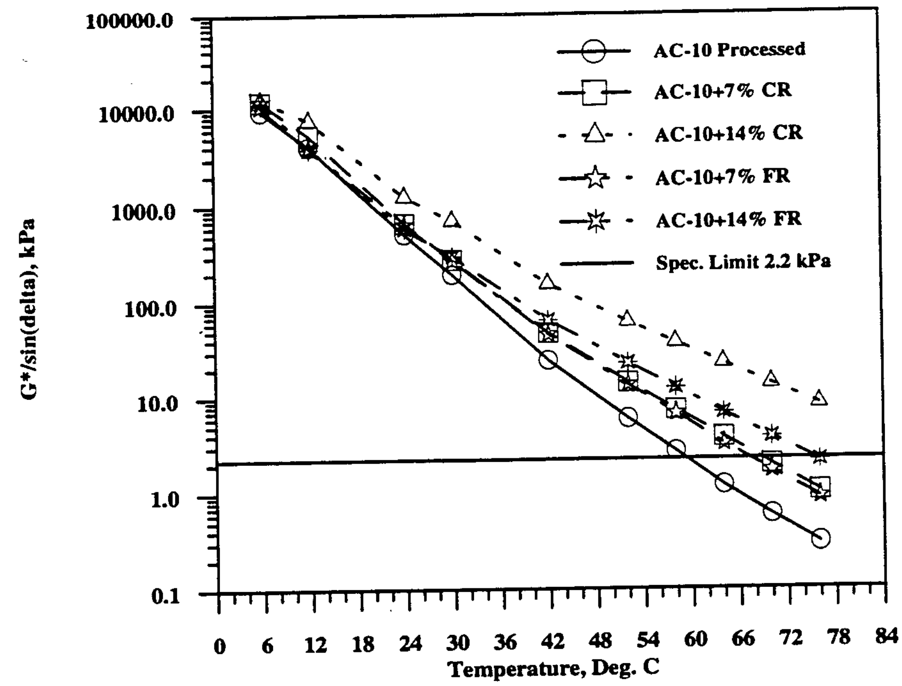

Figure 5-4 G*/sinδ versus temperature for RTFO aged AC-10 and modified binders

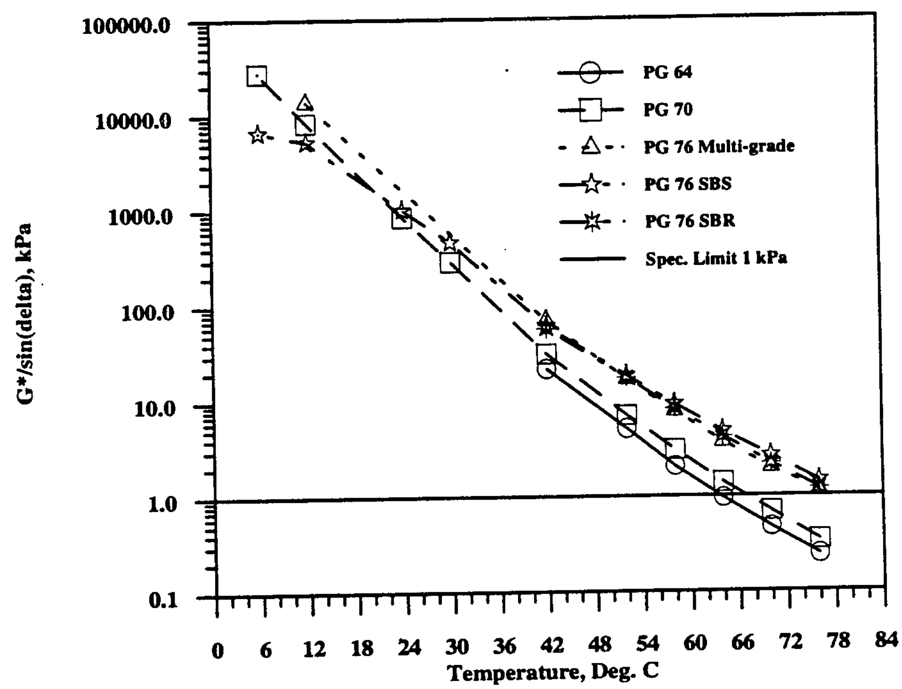

Figure 5-5 G*/sinδ versus temperature for unaged PG graded binders

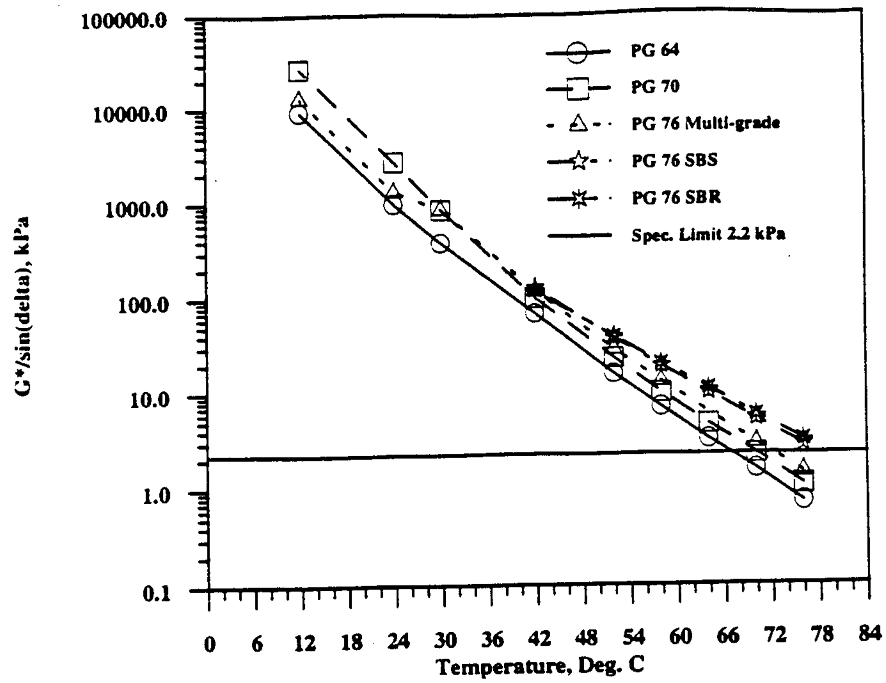

Figure 5-6 G*/sinδ versus temperature for RTFO aged PG graded binders

5.1.3 Comparison of Unmodified and Modified Binders Having Same PG Grading

Table 5-6 shows the modified and unmodified binders which have same PG grading. A question of particular interest is, do the different modified and unmodified binders having the same performance grade exhibit similar rheological characteristics over a wide range in temperature?

Figures 5-7 through 5-9 show the G*/sinδ stiffness value as a function of temperature for the PG 64-y, PG 70-y, and PG 76-y graded modified and unmodified binders, respectively. The following observation can be noted from these figures:

1. In the high temperature range (more than 42°C) the behavior of different unmodified and modified binders appear to be similar, especially the modified binders containing the same base asphalt.

2. In the intermediate/low temperature range, these same binders appear to behave differently. The PG 76-22 Multi-grade and SBS modified binders having same low temperature grade (-22°C) show different characteristics. Crumb rubber modified binders seem to approach the stiffness of the base asphalt at lower temperatures. Figures 5-1 through 5-4 substantiate this observation where at 6°C the stiffness values generally converge for all modified binders containing the same base asphalt cement.
3. It is possible that the low temperature grading for crumb rubber modified binders containing AC-20 and AC-10 will likely be different due to the varying stiffness behavior over the temperature range.

Table 5-6 Comparison of binders having same PG grade

Binder Type	PG Grade
AC-20 Processed	PG 64-y
AC-10+7% CR	PG 64-y
AC-10+7% FR	PG 64-y
PG 64-22	PG 64-y
AC-20+7% CR	PG 70-y
AC-20+7% FR	PG 70-y
AC-10+14% FR	PG 70-y
AC-20+14% CR	PG 76-y
AC-20+14% FR	PG 76-y
AC-10+14% CR	PG 76-y
PG 76-22 SBS modified	PG 76-y SBS
PG 76-22 SBR modified	PG 76-y SBR
PG 76-22 Multi-grade	PG 76-y Multi-grade

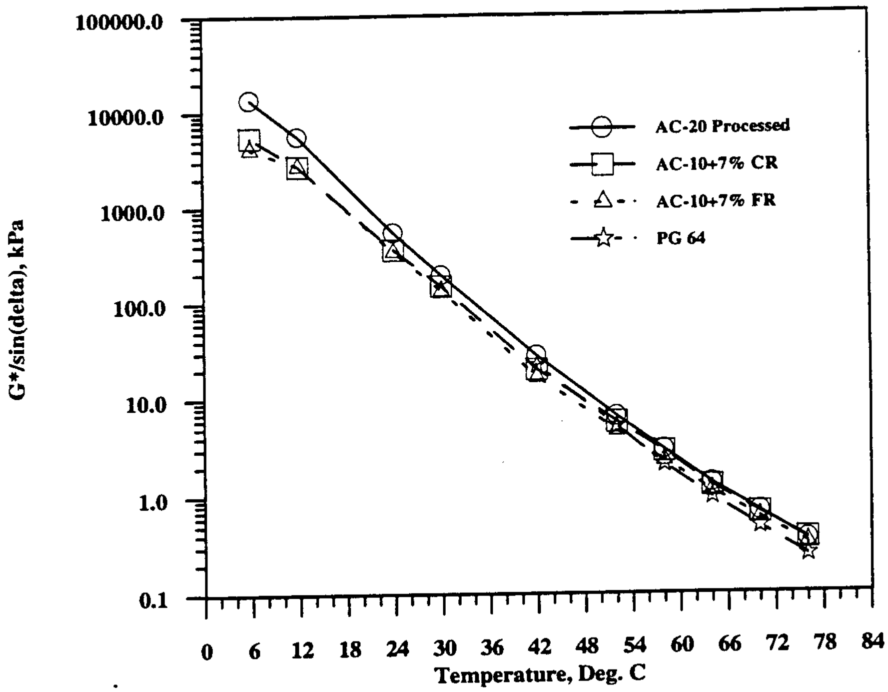

Figure 5-7 Comparison of PG 64-y graded binders

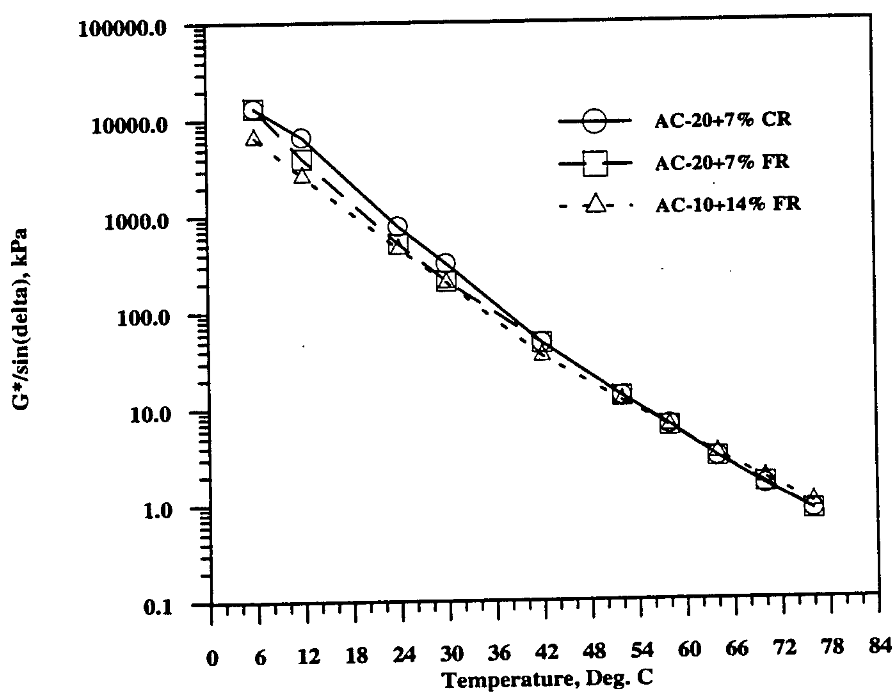

Figure 5-8 Comparison of PG 70-y graded binders

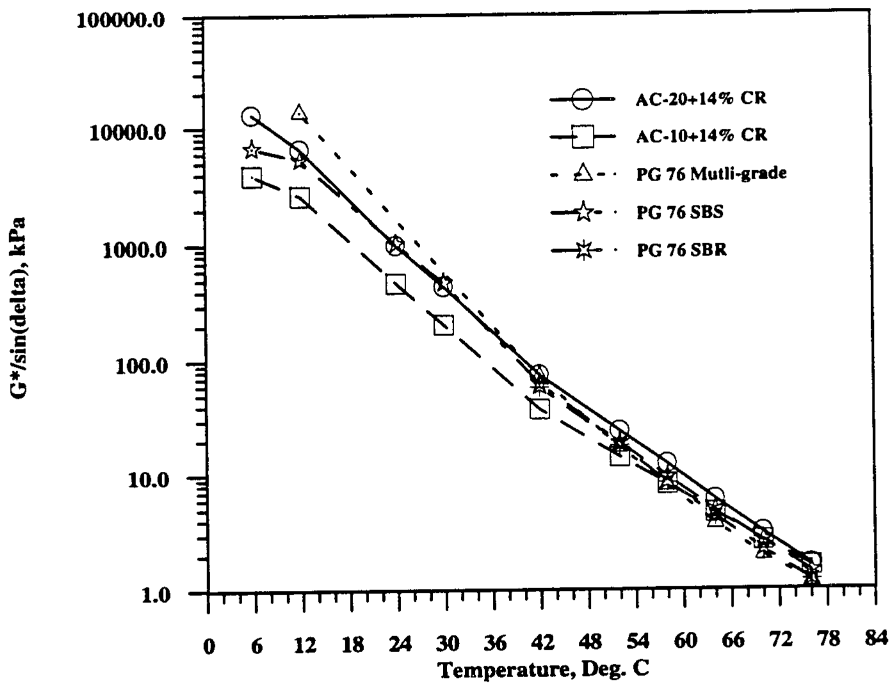

Figure 5-9 Comparison of PG 76-y graded binders

5.1.4 Effect of Crumb Rubber Concentration on the PG Grading of AC-20 and AC-10 Asphalts

Based on the test results, it was concluded in earlier sections that addition of 7% and 14% crumb rubber corresponds to an increase of one and two PG grades for the two crumb rubber concentrations, respectively. Figure 5-10 shows the relationship between the limiting temperature (the temperature at which 1 kPa value of G*/sinδ is attained for unaged binders) and the crumb rubber concentration for both AC-20 and AC-10 modified binders. The following observations can be made from these relationships:

1. In general, both AC-10 and AC-20 asphalt cements benefit equally by the addition of crumb rubber.
2. For the given crumb rubber particle sizes, these relationships can be used to estimate the concentration of the crumb rubber to attain a given PG grading. For example, both the AC-20 and AC-10 asphalts (PG 64-y and PG 58-y) will attain one higher grade (PG 70-y and PG 64-y, respectively) with the addition of only 5% crumb rubber as compared to 7% used in this study.

If the cost of the rubber was a major concern, it could provide a substantial benefit in savings. Similarly, both the base asphalts will attain two PG grades with the addition of only 10% crumb rubber as compared to 14% used in this study. The Rotational Viscosity test results, (Table 3-6), indicated that the 14% modification of AC-20 increased the viscosity of the modified binders beyond that specified by the Superpave™ binder specification, making them unsuitable for use inspite of having a higher PG grade. Similarly, viscosity tests should be conducted on the 10% crumb rubber modification of the AC-20 asphalt binder to verify the actual benefits associated with the use of higher percentage modification of asphalt binders.

3. Conversely, if the purpose of crumb rubber modification was to include as much rubber in the asphalt as possible (as was previously mandated by ISTEA), then, Figure 5-10 indicates that as much as 4 to 4.5% crumb rubber can be incorporated in the asphalt without changing the PG grade. This in itself may be the shortcoming for the performance graded specification because, for the same PG grading, the performance of the unmodified and crumb rubber modified binders may significantly be different.

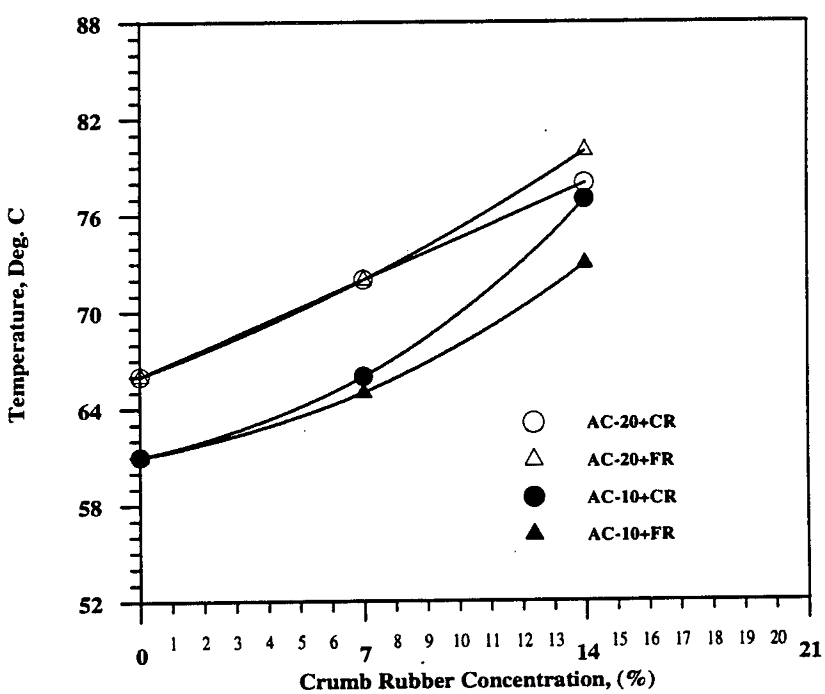

Figure 5-10 Effect of crumb rubber concentration on the PG grading

5.1.5 Effect of Frequency on the PG Grading of Unmodified and Modified Binders

The Superpave™ specifications grade the asphalt binders at a frequency of 10 radians per second (1.59 Hz) which corresponds to an average speed of approximately 50-60 mph. For slower moving traffic, it is suggested that the binder grade be increased by one grade (one grade warmer). For standing traffic it is suggested that binder grade be increased by two grades [3]. In order to verify these recommendations for modified binders, relationships for frequency (speed) and the PG grading limiting temperature (temperature at which the 1 kPa and 2.2 kPa value for $G^*/\sin\delta$ is achieved for unaged and RTFO aged binder) are shown in Figures 5-11 through 5-16. Results indicate that the Superpave™ recommendations do apply to the modified binders also. For example, if an asphalt binder grade selection for normal transient speed (1.59 Hz frequency) was AC-20 (PG 64-y), then reduction in frequency to 0.8 Hz would indicate the use of AC-20+7% CR or AC-20+7% FR (PG 70-y) grade of asphalt. For very slow traffic it would correspond to AC-20+14% CR or AC-20+14% FR (PG 76-y). These results indicate that based on Superpave™ binder specifications, crumb rubber modified binders may be effective in controlling high temperature distress (rutting) in pavements subjected to slow or standing design traffic.

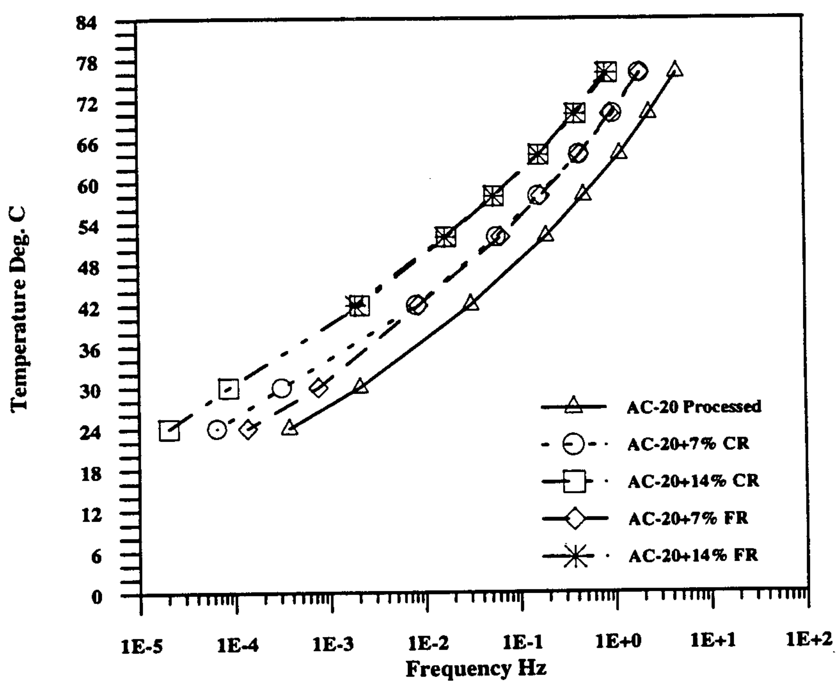

Figure 5-11 Limiting temperature versus frequency, unaged AC-20 and modified binders

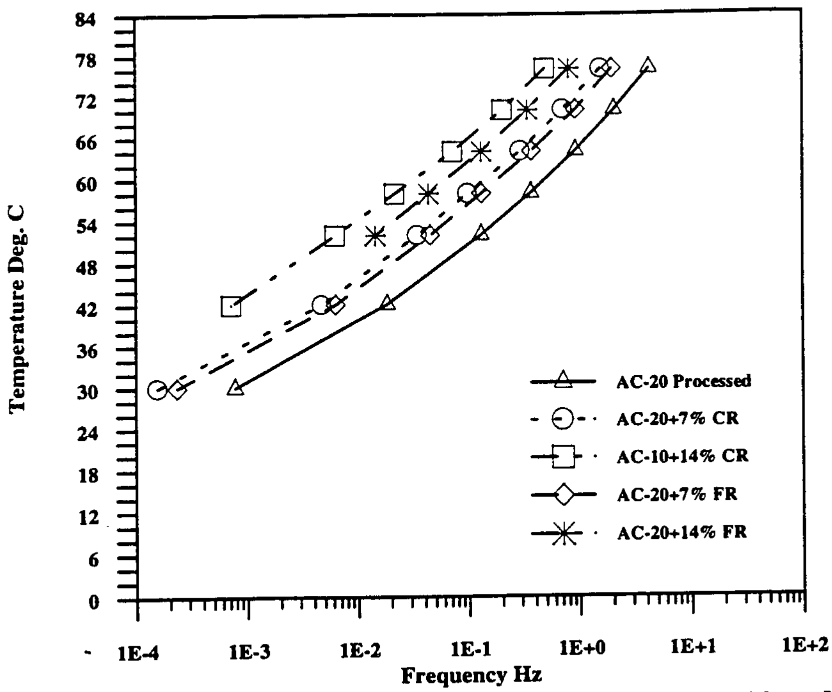

Figure 5-12 Limiting temperature versus frequency, RTFO aged AC-20 and modified binders

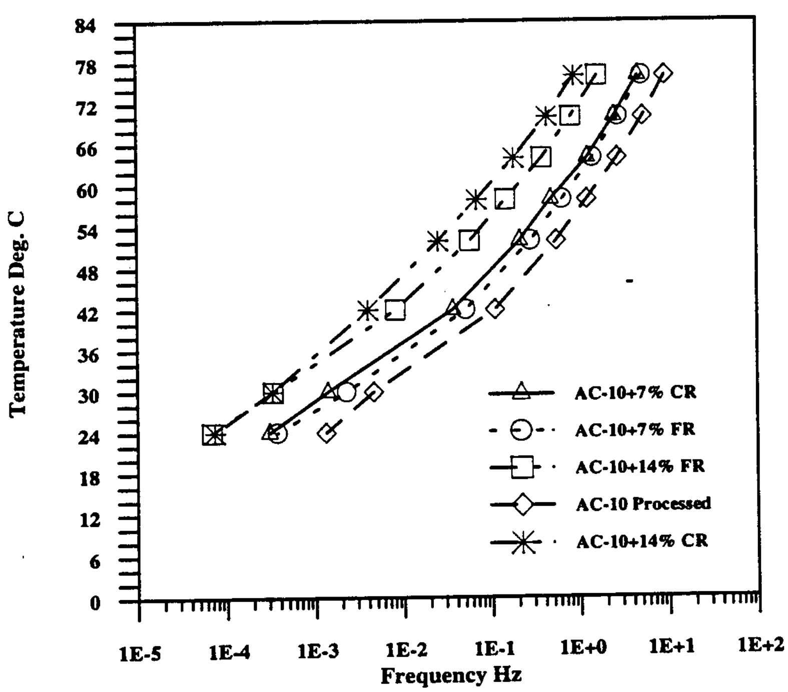

Figure 5-13 Limiting temperature versus frequency, unaged AC-10 and modified binders

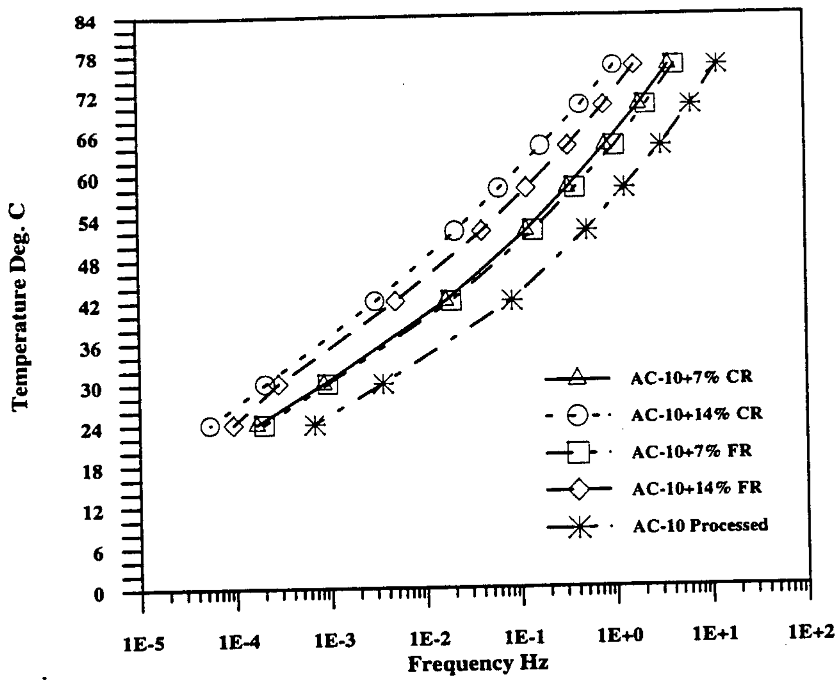

Figure 5-14 Limiting temperature versus frequency, RTFO aged AC-10 and modified binders

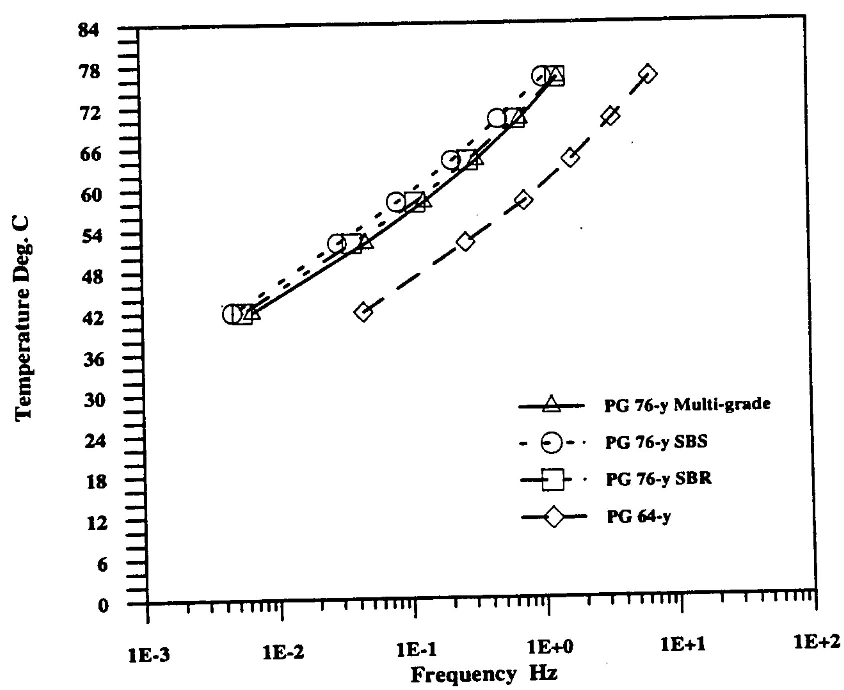

Figure 5-15 Limiting temperature versus frequency, unaged PG and modified binders

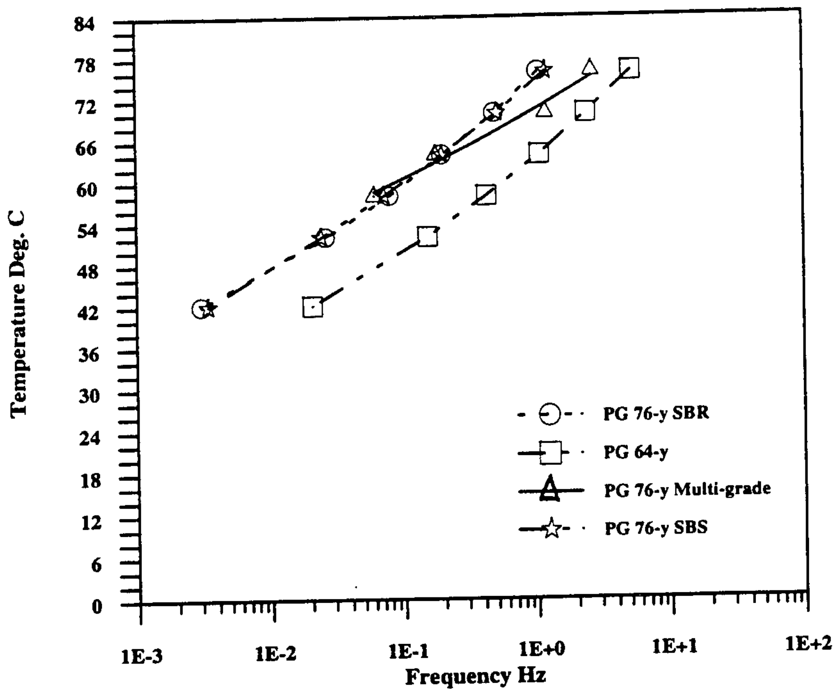

Figure 5-16 Limiting temperature versus frequency, RTFO aged and modified binders

5.2 Summary

The objective of this task was to characterize the modified asphalt binders over a range of frequencies and temperatures. The coefficient of variation in this task is higher as compared to Task A. This difference can be attributed to the limitation of the DSR research package in testing asphalt binders at lower temperatures. This is perhaps the reason due to which the desired strain levels could not be achieved for most of the modified asphalt binders at lower temperatures.

In general, the effect of 7% crumb rubber concentration was to increase the performance grade of the binder by one PG grade. A crumb rubber concentration of 14% resulted in an increase of the performance grade of the binder by two PG grades. For the AC-20 asphalt, the crumb rubber particle size per-se did not have any influence on the performance grading. For the AC-10 asphalt, at higher concentrations of 14%, the crumb rubber particle size affected the PG grading.

Test results presented in Figure 5.10 indicate that both AC-20 and AC-10 asphalts can achieve one and two higher PG grades with as little as 5% and 10% crumb rubber modification, respectively, as opposed to the 7% and 14% used in this study. Test results indicate that AC-20 and AC-10 binders' performance grade will not change when less than 5% crumb rubber modification is used. Direct comparison of the rheological characteristics of the unmodified and modified binders over a range in temperature indicate that binders with same PG grade may behave differently.

Results of this study indicate that the Superpave™ recommendation of increasing PG grade of binder on the warmer side, for slow and standing design traffic loading is also applicable to the crumb rubber modified binders. Based on the rheological characteristics, it appears that in an environment with wide temperature range, the AC-10 crumb rubber modified binder may perform better than the AC-20 binder (AC-20 and AC-10+7% CR or FR have the same PG 64-y performance grading).

6. Summary and Conclusions

This study investigated two aspects of the performance related Superpave™ binder specification methodology -- applicability of the DSR to crumb rubber modified binders, and effect of crumb rubber particle size and concentration on the higher temperature performance grading of asphalt cements commonly used in North Carolina. In addition, physical characteristics of 5 more performance graded unmodified and modified binders were evaluated over a range of frequencies and temperatures.

The hypothesis investigated was that, if the crumb rubber particle size and concentration interfered with the DSR test measurements, varying the film thickness of the binder specimen should significantly affect the measured properties. In order to validate this hypothesis, two binder film thicknesses were used. At low temperature, 2 mm and 4 mm film thicknesses were evaluated. For medium and high temperatures, 1 mm and 2 mm film thicknesses were evaluated.

Test results indicate that the overall average coefficient of variation due to the use of different specimen film thickness and replicate testing were 6.2% and 6.5%, respectively. Based on these results, it can be concluded that for the crumb rubber particle size and concentrations used, the AASHTO TP5 test protocol is applicable to the modified binders used in this study.

Unmodified and modified binders were characterized over a range in frequency and temperature using the AASHTO TP5 test protocol and the DSR research package. In general, test results indicate that the variability due to replicate testing using the research package was much higher than the Superpave™ specified DSR test package. Much of the variability was observed to be associated with the low temperature testing (use of the 8 mm diameter spindle size, and temperatures below 24°C). The crumb rubber modified RTFO and PAV aged binders, at low temperatures were so stiff that testing could not be conducted at a reasonable strain value, due to the limitation of the DSR.

Based on the experience obtained from this study, it is the opinion of the authors that much of the variation in test results could be minimized as follows:

1. It was observed during the duration of this study that the variability in test results was systematically reduced as the DSR operator gained more training and experience in setting up specimens, especially for the 8 mm diameter specimens.
2. Variability seemed to decrease with the use of silicon molds supplied by the Asphalt Institute for preparation of the test specimens.
3. AASHTO TP5 test protocol suggest a range of strain (or stress) levels which may be used for testing. Test results indicate that at any temperature, a sufficiently high strain level (in the linear viscoelastic limit defined by the protocol) must be used in order to get repeatable results. On the other hand, some modified PAV aged binders at low temperatures could not be tested at acceptable strain levels to get any meaningful results.

Specific conclusions based on the results of this study are as follows:

1. The coefficient of variation for test results increased slightly for the crumb rubber modified binders used in this study. Based on the overall coefficient of variation of approximately 6.5% for the unmodified and modified binders tested, it appears that the AASHTO TP5 test protocol is applicable to the modified binders used in this study.
2. The coefficient of variation obtained when using the DSR research package is much higher as compared to the DSR Superpave™ test package.
3. For both AC-20 and AC-10 asphalts, addition of 7% crumb rubber (coarse and fine crumb rubber) produced one higher performance grade jump; i.e., from PG 64-y and PG 58-y to PG 70-y and PG 64-y, respectively.
4. The NCDOT test results indicate that AC-20 asphalt modified with 7% crumb rubber has a grade of PG 70-22.
5. For AC-20 asphalt, addition of 14% crumb rubber (coarse and fine rubber) produced two higher performance grade jump; i.e., from PG 64-y to PG 76-y.
6. The NCDOT test results indicate that the viscosity of the 14% crumb rubber modified AC-20

asphalt exceeds the Superpave™ binder specified criteria, and thus may not be suitable for use.

7. For AC-10 asphalt cement, addition of 14% coarse rubber produced three higher performance grade jumps; i.e., from PG 58-y to PG 76-y, whereas the addition of 14% fine rubber produced a two grade jump from PG 58-y to PG 70-y.
8. Except for one binder, the high temperature performance grading of the PG binders were confirmed. The PG 70-22 binder failed to achieve the 1 kPa value for the $G^*/\sin\delta$, although it did barely meet the 2.2 kPa value after RTFO aging.
9. The addition of 7% coarse and fine crumb rubber produced a one higher performance grade jump over the base asphalt cements. Results suggest that as low as 5% crumb rubber modification will have a similar effect on the performance grading of both AC-20 and AC-10 modified binders. Similarly, as little as 10% crumb rubber will have the same effect of increasing performance grade by two jumps as compared to the 14% used in this study.
10. In the high temperature range (more than 42°C) the behavior of different unmodified and modified binders appear to be similar, especially the modified binders containing the same base asphalt.
11. In the intermediate/low temperature range, these same binders appear to behave differently. The PG 76-22 Multi-grade and SBS modified binders having same low temperature grade (-22°C) show different characteristics. Crumb rubber modified binders seems to approach the stiffness of the base asphalt at lower temperatures.

Relationships between the limiting temperature (temperature at which the $G^*/\sin\delta$ value of 1 kPa is reached) and the fine and coarse crumb rubber concentrations were developed. These relationships can be used as a guide to specify and produce crumb rubber modified binders which meet specific performance grading requirements. Based on the results of this study, it appears that for all conditions being the same, an AC-10 asphalt cement modified with 5% to 7% crumb rubber will perform equal to or better than the AC-20 unmodified binder over a range of temperature.

7. Implementation and Technology Transfer Plan

The objectives of this study were to examine the applicability of the current Superpave™ DSR testing protocol developed for unmodified asphalt binders to the crumb rubber and other modified binders. Results of this study indicated that within the range of the crumb rubber concentration and particle size used in this study, the current AASHTO TP5 test protocol is applicable to the modified binders without any modification to the protocol.

For the temperature range for which the $G^*/\sin\delta$ values will not be much lower than 1 kPa, no changes in test protocol is necessary for implementation of the current Superpave™ PG grading protocol applied to the crumb rubber modified binders.

8. References

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Appendix A1

Results for subtask A1

AC-20 PROCESSED
TEMPERATURE 70° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin (δ) (Pa)	G *sin(δ) (Pa)
1	2	6.40E+02	85.1	6.40E+02	6.38E+02
2		1.48E+03	82.5	1.50E+03	1.47E+03
1	5	6.14E+02	85.7	6.16E+02	6.12E+02
2		1.47E+03	82.0	1.49E+03	1.46E+03
1	10	6.25E+02	85.5	6.27E+02	6.23E+02
2		1.44E+03	82.0	1.46E+03	1.43E+03
1	15	6.25E+02	85.9	6.26E+02	6.23E+02
2		1.36E+03	82.4	1.37E+03	1.35E+03
1	20	6.08E+02	85.4	6.10E+02	6.06E+02
2		1.32E+03	82.4	1.33E+03	1.31E+03

TEMPERATURE 58° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sinδ) (Pa)	G *sin(δ) (Pa)
1	2	2.87E+03	81.6	2.90E+03	2.84E+03
2		2.70E+03	81.7	2.73E+03	2.67E+03
1	5	2.54E+03	81.8	2.57E+03	2.51E+03
2		2.64E+03	81.8	2.67E+03	2.61E+03
1	10	2.50E+03	82.3	2.53E+03	2.48E+03
2		2.60E+03	82.3	2.63E+03	2.58E+03
1	15	2.50E+03	81.9	2.53E+03	2.47E+03
2		2.60E+03	82.3	2.62E+03	2.58E+03
1	20	2.56E+03	82.1	2.59E+03	2.54E+03
2		2.55E+03	82.2	2.57E+03	2.53E+03

AC-20 PROCESSED
TEMPERATURE 42° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
1	2	2.24E+04	74.7	2.32E+04	2.16E+04
2		2.00E+04	75.7	2.05E+04	1.94E+04
1	5	2.26E+04	75.1	2.34E+04	2.18E+04
2		2.00E+04	75.3	2.07E+04	1.93E+04
1	10	2.14E+04	75.5	2.21E+04	2.07E+04
2		2.03E+03	75.7	2.09E+04	1.97E+03
1	15	2.12E+04	75.3	2.20E+04	2.05E+04
2		2.06E+04	75.7	2.12E+04	2.00E+04
1*	20	2.10E+04	75.1	2.18E+04	2.03E+04
2*		2.06E+04	75.6	2.13E+04	1.99E+04

TEMPERATURE 24° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
2	2	5.23E+05	71.0	5.53E+05	4.94E+05
4		7.00E+05	66.7	7.62E+05	6.43E+05
2	5	5.24E+05	66.5	5.72E+05	4.81E+05
4		7.00E+05	66.8	7.62E+05	6.43E+05
2	10	5.04E+05	67.1	5.47E+05	4.64E+05
4		6.60E+05	67.4	7.15E+05	6.09E+05
2	15	4.76E+05	67.7	5.15E+05	4.40E+05
4		6.55E+05	70.8	6.94E+05	6.18E+05
2	20	4.37E+05	68.3	4.70E+05	4.06E+05
4		--	--	--	--

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

AC-20 PROCESSED
TEMPERATURE 12° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
2	2	2.23E+06	59.2	2.59E+06	1.91E+06
4		1.49E+06	63.3	1.66E+06	1.33E+06
2*	5 (3.7)	2.63E+06	58.8	3.08E+06	2.25E+06
4		1.44E+06	62.9	1.62E+06	1.28E+06
2*	10 (3.7)	2.65E+06	58.5	3.10E+06	2.26E+06
4*	(7.0)	1.42E+06	63.2	1.60E+06	1.27E+06
2*	15 (3.68)	2.65E+06	58.5	3.11E+06	2.26E+06
4*	(7.0)	1.43E+06	63.0	1.60E+06	1.27E+06
2*	20 (3.63)	2.67E+06	58.5	3.13E+06	2.28E+06
4*	(7.0)	1.42E+06	63.4	1.59E+06	1.27E+06

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

AC-20 + 14% FINE RUBBER
TEMPERATURE 70° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
1	2	4.13E+03	72.3	4.33E+03	3.93E+03
2		3.74E+03	73.8	3.90E+03	3.59E+03
1	5	4.03E+03	72.8	4.23E+03	3.85E+03
2		3.56E+03	74.8	3.70E+03	3.43E+03
1	10	4.00E+03	73.3	4.12E+03	3.83E+03
2		3.44E+03	74.9	3.56E+03	3.32E+03
1	15	3.73E+03	74.2	3.87E+03	3.59E+03
2		3.54E+03	75.3	3.65E+03	3.42E+03
1	20	3.92E+03	73.9	4.08E+03	3.77E+03
2		3.54E+03	75.7	3.65E+03	3.43E+03

TEMPERATURE 58° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
1	2	1.27E+04	64.8	1.40E+04	1.14E+04
2		--	--	--	--
1	5	1.21E+04	65.1	1.34E+04	1.10E+04
2		1.23E+04	65.3	1.36E+04	1.12E+04
1	10	1.22E+04	65.5	1.34E+04	1.11E+04
2		1.22E+04	65.7	1.34E+04	1.11E+04
1	15	1.20E+04	66.1	1.31E+04	1.10E+04
2		1.22E+04	66.6	1.33E+04	1.12E+04
1	20	1.18E+04	66.7	1.30E+04	1.08E+04
2		1.22E+04	67.2	1.32E+04	1.12E+04

AC-20 + 14% FINE RUBBER
TEMPERATURE 42° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
1	2	6.84E+04	54.9	8.36E+04	5.59E+04
2		--	--	--	--
1*	5 (4.73)	6.82E+04	55.1	8.32E+04	5.59E+04
2*	(4.88)	6.15E+04	56.3	7.40E+04	5.11E+04
1*	10 (4.77)	6.76E+04	55.2	8.23E+04	5.55E+04
2*	(5.22)	6.20E+04	56.6	7.40E+04	5.17E+04
1*	15 (4.74)	6.80E+04	55.5	8.26E+04	5.60E+04
2*	(5.24)	6.16E+04	56.3	7.40E+04	5.12E+04
1*	20 (4.77)	6.77E+04	55.5	8.21E+04	5.58E+04
2*	. (5.27)	6.13E+04	56.7	7.33E+04	5.12E+04

TEMPERATURE 24° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
2	2	6.44E+04	58.0	2.32E+04	7.60E+04
4		7.51E+05	56.6	2.05E+04	9.00E+05
2	5	2.83E+05	55.1	2.34E+04	1.08E+06
4		8.10E+05	55.5	2.07E+04	9.83E+05
2	10	7.53E+05	55.9	2.21E+04	9.09E+05
4		7.76E+05	56.2	2.09E+04	9.34E+05
2*	15 (12.76)	7.57E+05	56.3	2.20E+04	9.11E+05
4*	(12.96)	7.48E+00	56.6	2.12E+04	8.97E+05
2*	20 (12.67)	7.74E+05	56.0	2.18E+04	9.33E+05
4*	(12.97)	7.60E+05	56.3	2.13E+04	9.14E+05

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

AC-20 +14 % COARSE RUBBER
TEMPERATURE 70° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
1	2	4.14E+03	70.5	4.38E+03	3.90E+03
2		3.57E+03	72.5	3.74E+03	3.40E+03
1	5	3.92E+03	71.5	4.14E+03	3.72E+03
2		3.30E+03	73.2	3.46E+03	3.16E+03
1	10	3.90E+03	71.6	4.09E+03	3.70E+03
2		3.30E+03	74.0	3.40E+03	3.17E+03
1	15	8.04E+03	66.2	8.90E+03	7.35E+03
2		3.17E+03	74.5	3.30E+03	3.05E+03
1	20	3.60E+03	72.9	3.76E+03	3.44E+03
2		3.15E+03	74.7	3.30E+03	3.04E+03

TEMPERATURE 58° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
1	2	1.12E+04	63.4	1.26E+04	1.00E+04
2		7.50E+03	60.9	8.60E+03	6.55E+03
1	5	1.16E+04	63.1	1.30E+04	1.03E+04
2		1.45E+04	61.0	1.66E+04	1.27E+04
1	10	1.16E+04	63.4	1.30E+04	1.04E+04
2		1.45E+04	61.9	1.64E+04	1.28E+04
1	15	1.18E+04	64.0	1.30E+04	1.06E+04
2		1.42E+04	62.3	1.60E+04	1.26E+04
1	20	1.17E+04	65.2	1.29E+04	1.06E+04
2		1.36E+04	63.8	1.50E+04	1.22E+04

AC-20 + 14 % COARSE RUBBER
TEMPERATURE 42° C

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)
1	2	5.64E+04	55.2	6.87E+04	4.63E+04
2		4.96E+04	54.6	6.08E+04	4.04E+04
1	5	5.60E+04	55.4	6.80E+04	4.61E+04
2		5.13E+04	54.4	6.32E+04	4.17E+04
1*	10 (5.74)	5.62E+04	55.2	6.85E+04	4.61E+04
2*	(6.33)	5.10E+04	54.1	6.30E+04	4.13E+04
1*	15 (5.7)	5.60E+04	55.2	6.83E+04	4.60E+04
2*	(5.76)	5.16E+04	54.3	6.35E+04	4.19E+04
1*	20 (5.74)	5.62E+04	55.4	6.83E+04	4.62E+04
2*	. (6.21)	5.20E+04	54.2	6.41E+04	4.22E+04

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

Appendix A2

Results for subtask A2

TEMPERATURE 70° C

AC-20 PROCESSED

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
2	2	6.87E+02	85.60	6.90E+02	6.85E+02	1.98	70.10
	5	6.69E+02	85.30	6.71E+02	6.67E+02	5.00	70.00
	10	6.70E+02	85.30	6.73E+02	6.68E+02	10.18	70.00
	15	6.77E+02	85.40	6.79E+02	6.75E+02	14.85	70.00
	20	6.64E+02	85.40	6.66E+02	6.62E+02	20.22	69.90
1	2	6.43E+02	86.20	6.45E+02	6.42E+02	1.94	69.90
	5	6.00E+02	85.50	6.02E+02	5.98E+02	5.02	70.00
	10	5.84E+02	85.60	5.86E+02	5.82E+02	10.29	70.00
	15	5.80E+02	85.40	5.81E+02	5.78E+02	14.92	70.10
	20	5.69E+02	85.60	5.70E+02	5.67E+02	20.29	70.00
REPEAT							
2	2	6.96E+02	84.90	6.99E+02	6.93E+02	2.07	70.00
	5	7.29E+02	85.40	7.32E+02	7.27E+02	4.93	70.10
	10	7.20E+02	85.00	7.23E+02	7.17E+02	9.93	70.00
	15	7.18E+02	85.30	7.20E+02	7.16E+02	15.31	69.90
	20	7.35E+02	85.30	7.37E+02	7.32E+02	20.06	70.00
1	2	7.45E+02	84.90	7.48E+02	7.42E+02	2.09	70.10
	5	7.58E+02	84.80	7.61E+02	7.55E+02	5.19	69.90
	10	8.00E+02	85.10	8.03E+02	7.97E+02	9.60	70.10
	15	7.73E+02	85.40	7.75E+02	7.70E+02	14.68	69.90
	20	7.32E+02	85.50	7.35E+02	7.30E+02	19.94	70.00

TEMPERATURE 42° C

AC-20 PROCESSED

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
2	2	2.96E+04	74.60	3.07E+04	2.85E+04	2.01	42.00
	5	2.89E+04	75.10	2.99E+04	2.79E+04	4.98	42.00
	10	2.94E+04	74.70	3.05E+04	2.84E+04	9.59	42.00
	15	2.90E+04	74.80	3.00E+04	2.80E+04	11.12*	42.00
	20	2.87E+04	74.90	2.97E+04	2.77E+04	11.26*	42.00
1	2	2.80E+04	74.70	2.90E+04	2.70E+04	2.02	42.00
	5	2.83E+04	74.70	2.93E+04	2.73E+04	5.03	41.90
	10	2.84E+04	74.40	2.95E+04	2.73E+04	9.63	42.00
	15	2.86E+04	74.90	2.95E+04	2.76E+04	11.3*	42.00
	20	3.00E+04	74.70	3.12E+04	2.89E+04	10.79*	41.90
REPEAT							
2	2	2.93E+04	75.40	3.04E+04	2.83E+04	2.03	42.00
	5	2.84E+04	75.30	2.94E+04	2.75E+04	5.17	42.00
	10	2.77E+04	75.20	2.86E+04	2.68E+04	10.07	42.00
	15	2.74E+04	75.00	2.84E+04	2.65E+04	11.77*	42.00
	20	2.72E+04	75.00	2.82E+04	2.63E+04	11.87*	42.00
1	2	2.74E+04	74.60	2.85E+04	2.64E+04	2.00	42.00
	5	2.92E+00	74.60	3.03E+04	2.82E+00	4.90	42.00
	10	2.88E+04	74.60	2.99E+04	2.78E+04	10.30	42.00
	15	2.77E+04	75.00	2.87E+04	2.68E+04	11.65*	42.00
	20	2.80E+04	74.60	2.91E+04	2.70E+04	11.49*	41.90

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

TEMPERATURE 12° C

AC-20 PROCESSED

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
4	2	4.77E+06	55.80	3.95E+06	5.77E+06	2.07*	12.00
	5	4.84E+06	55.80	4.00E+06	5.85E+06	2.04*	12.00
	10	4.86E+06	55.70	4.00E+06	5.89E+06	2.03*	12.10
	15	4.90E+06	55.60	4.05E+06	5.94E+06	2.01*	11.90
	20	4.82E+06	55.60	3.98E+06	5.84E+06	2.04*	12.00
2	2	5.44E+06	55.40	4.48E+06	6.61E+06	1.81*	12.00
	5	5.41E+06	55.50	4.46E+06	6.57E+06	1.82*	12.00
	10	5.41E+06	55.20	4.45E+06	6.59E+06	1.82*	12.00
	15	5.34E+06	55.10	4.38E+06	6.51E+06	1.85*	12.00
	20	5.30E+06	56.30	4.40E+06	6.37E+06	1.86*	12.10
REPEAT							
4	2	5190000	55.40	4270000	6.31E+06	1.9*	12.00
	5	5.30E+06	55.60	4.37E+06	6.43E+06	1.86*	12.00
	10	5.30E+06	55.50	4.40E+06	6.43E+06	1.86*	12.00
	15	5.35E+06	55.30	4.40E+06	6.51E+06	1.84*	12.00
	20	5.44E+06	55.50	4.48E+06	6.60E+06	1.81*	12.00
2	2	5.38E+06	55.00	4.40E+06	6.57E+06	1.83*	12.00
	5	5.57E+06	54.60	4.54E+06	6.84E+06	1.77*	11.90
	10	5.58E+06	54.40	4.54E+06	6.86E+06	1.77*	12.00
	15	5.62E+06	54.70	4.59E+06	6.89E+06	1.75*	12.00
	20	--	--	--	--	--	--

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude limit was used.

TEMPERATURE 70° C

AC-20 + 7% COARSE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
2	2	1.60E+03	80.30	1.62E+03	1.58E+03	1.98	70.00
	5	1.68E+03	80.80	1.70E+03	1.66E+03	4.93	70.10
	10	1.61E+03	80.40	1.63E+03	1.59E+03	9.72	69.90
	15	1.56E+03	81.10	1.58E+03	1.54E+03	15.08	70.00
	20	1.55E+03	79.80	1.57E+03	1.53E+03	20.44	70.10
1	2	1.65E+03	79.90	1.68E+03	1.62E+03	2.08	70.10
	5	1.71E+03	80.40	1.74E+03	1.69E+03	4.99	70.00
	10	1.74E+03	80.80	1.76E+03	1.72E+03	9.80	70.00
	15	1.68E+03	80.60	1.70E+03	1.66E+03	14.71	70.00
	20	1.62E+03	80.80	1.64E+03	1.60E+03	20.08	70.00
REPEAT							
2	2	1.53E+03	79.20	1.56E+03	1.51E+03	2.01	70.00
	5	1.50E+03	79.40	1.53E+03	1.47E+03	5.05	70.00
	10	1.48E+03	79.50	1.51E+03	1.46E+03	10.24	70.00
	15	1.51E+03	79.50	1.54E+03	1.48E+03	14.90	70.00
	20	1.48E+03	80.00	1.50E+03	1.46E+03	20.14	70.00
1	2	1.32E+03	80.90	1.34E+03	1.30E+03	1.98	70.00
	5	1.36E+03	80.50	1.38E+03	1.34E+03	4.76	70.00
	10	1.27E+03	80.30	1.30E+03	1.25E+03	10.12	70.00
	15	1.30E+03	80.50	1.32E+03	1.28E+03	14.89	70.00
	20	1.30E+03	80.90	1.32E+03	1.28E+03	19.81	70.10

TEMPERATURE 42° C

AC-20+ 7% COARSE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (°C)
2	2	5.74E+04	63.60	6.41E+04	5.14E+04	1.98	42.00
	5	5.71E+04	63.70	6.37E+04	5.12E+04	5.09	42.00
	10	5.80E+04	63.60	6.47E+04	5.19E+04	5.57*	42.00
	15	5.61E+04	64.00	6.24E+04	5.04E+04	5.75*	41.90
	20	5.48E+04	64.30	6.08E+04	4.94E+04	5.89*	42.00
1	2	4.60E+04	64.40	5.12E+04	4.15E+04	1.97	42.00
	5	4.61E+04	64.40	5.12E+04	4.16E+04	4.95	42.00
	10	4.51E+04	64.60	5.00E+04	4.07E+04	7.15*	42.00
	15	4.49E+04	64.50	4.98E+04	4.05E+04	7.18*	41.90
	20	4.45E+04	64.20	4.94E+04	4.01E+04	7.25*	42.00
REPEAT							
2	2	5.65E+04	63.10	6.33E+04	5.04E+04	2.02	42.00
	5	5.55E+04	63.40	6.21E+04	4.96E+04	5.12	42.00
	10	5.63E+04	63.40	6.29E+04	5.03E+04	5.74*	42.00
	15	5.56E+04	63.50	6.21E+04	4.97E+04	5.81*	42.00
	20	5.54E+04	63.40	6.19E+04	4.95E+04	5.83*	42.10
1	2	4.58E+04	63.70	5.10E+04	4.10E+04	2.00	42.00
	5	4.56E+04	63.60	5.09E+04	4.08E+04	4.96	42.00
	10	4.55E+04	63.80	5.08E+04	4.08E+04	7.08*	42.00
	15	4.59E+04	63.90	5.11E+04	4.12E+04	7.03*	42.10
	20	4.57E+04	63.90	5.09E+04	4.10E+04	7.07*	42.00

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

TEMPERATURE 12° C

AC-20 + 7% COARSE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
4	2	4.55E+06	51.20	3.55E+06	5.84E+06	2.16*	12.10
	5	4.54E+06	51.30	3.54E+06	5.82E+06	2.17*	12.00
	10	4.57E+06	51.10	3.56E+06	5.87E+06	2.16*	12.10
	15	4.59E+06	51.50	3.59E+06	5.87E+06	2.15*	12.10
	20	4.61E+06	51.50	3.61E+06	5.89E+06	2.14*	11.90
2	2	4.51E+06	51.50	3.53E+06	5.76E+06	2.01*	12.10
	5	4.51E+06	51.70	3.53E+06	5.75E+06	2.18*	12.00
	10	4.46E+06	51.60	3.49E+06	5.69E+06	2.21*	12.00
	15	4.47E+06	51.90	3.52E+06	5.68E+06	2.2*	12.00
	20	4.54E+06	51.50	3.55E+06	5.80E+06	2.17*	12.00
REPEAT							
4	2	4.66E+06	51.50	3.66E+06	5.96E+06	2.11*	12.00
	5	4.69E+06	51.80	3.68E+06	5.97E+06	2.1*	12.00
	10	4.75E+06	51.60	3.72E+06	6.06E+06	2.07*	12.00
	15	4.77E+06	51.90	3.75E+06	6.06E+06	2.06*	12.10
	20	4.81E+06	51.40	3.76E+06	6.16E+06	2.05*	12.00
2	2	4.52E+06	51.30	3.52E+06	5.79E+06	2.02	12.10
	5	4.46E+06	51.10	3.48E+06	5.73E+06	2.21*	12.00
	10	4.50E+06	51.50	3.52E+06	5.75E+06	2.19*	12.00
	15	4.63E+06	51.20	3.60E+06	5.94E+06	2.13*	11.90
	20	4.66E+06	51.00	3.62E+06	6.00E+06	2.11*	12.00

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude limit was used.

TEMPERATURE 70° C

AC-20 + 7% FINE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
2	2	1.53E+03	81.40	1.55E+03	1.51E+03	1.99	69.90
	5	1.53E+03	82.00	1.54E+03	1.51E+03	4.88	70.00
	10	1.46E+03	82.10	1.48E+03	1.45E+03	10.16	70.00
	15	1.48E+03	82.30	1.49E+03	1.46E+03	15.04	70.10
	20	1.46E+03	82.30	1.47E+03	1.45E+03	20.17	70.00
1	2	1.47E+03	82.40	1.48E+03	1.46E+03	1.99	69.90
	5	1.53E+03	82.20	1.55E+03	1.52E+03	4.94	70.00
	10	1.40E+03	82.30	1.41E+03	1.39E+03	10.24	70.10
	15	1.44E+03	82.50	1.45E+03	1.43E+03	14.92	70.00
	20	1.40E+03	82.10	1.42E+03	1.39E+03	20.16	70.00
REPEAT							
2	2	1.38E+03	81.80	1.39E+03	1.37E+03	2.04	70.00
	5	1.33E+03	82.20	1.35E+03	1.32E+03	5.19	70.00
	10	1.38E+03	82.50	1.39E+03	1.36E+03	9.90	70.10
	15	1.34E+03	82.60	1.35E+03	1.33E+03	15.10	70.10
	20	1.33E+03	82.60	1.34E+03	1.32E+03	20.11	70.10
1	2	1.35E+03	81.80	1.37E+03	1.34E+03	2.03	70.00
	5	1.38E+03	82.10	1.39E+03	1.37E+03	4.92	69.90
	10	1.38E+03	82.60	1.39E+03	1.37E+03	9.78	70.00
	15	1.34E+03	82.40	1.36E+03	1.33E+03	14.80	70.00
	20	1.31E+03	82.80	1.32E+03	1.30E+03	20.09	70.00

TEMPERATURE 42° C

AC-20 + 7% FINE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (°C)
2	2	5.05E+04	64.90	5.58E+04	4.57E+04	2.00	42.00
	5	5.01E+04	65.30	5.52E+04	4.55E+04	4.91	42.00
	10	4.96E+04	65.30	5.46E+04	4.51E+04	6.52*	42.00
	15	4.97E+04	65.10	5.48E+04	4.51E+04	6.5*	42.00
	20	4.97E+04	65.50	5.46E+04	4.52E+04	6.5*	42.00
1	2	4.19E+04	65.20	4.62E+04	3.80E+04	2.02	42.00
	5	4.21E+04	65.20	4.64E+04	3.82E+04	4.92	42.10
	10	4.23E+04	65.40	4.65E+04	3.85E+04	7.63*	42.00
	15	4.19E+04	65.00	4.57E+04	3.80E+04	7.8*	42.00
	·20	4.28E+04	65.00	4.72E+04	3.88E+04	7.55*	42.00
REPEAT							
2	2	4.94E+04	65.20	5.44E+04	4.48E+04	2.00	42.00
	5	4.84E+04	65.30	5.33E+04	4.40E+04	5.11	42.00
	10	4.60E+04	65.50	5.05E+04	4.18E+04	7.02*	42.00
	15	4.73E+04	65.70	5.19E+04	4.31E+04	6.83*	42.00
	20	4.62E+04	65.40	5.08E+04	4.20E+04	6.99*	42.00
1	2	4.34E+04	65.10	4.78E+04	3.94E+04	1.96	42.00
	5	4.25E+04	65.60	4.67E+04	3.87E+04	5.03	42.00
	10	4.27E+04	65.30	4.70E+04	3.88E+04	7.51	42.00
	15	4.27E+04	65.30	4.71E+04	3.88E+04	7.51	42.00
	20	4.31E+04	65.40	4.74E+04	3.92E+04	7.49*	42.00

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

TEMPERATURE 12° C

AC-20 + 7% FINE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
4	2	4.90E+06	52.40	3.88E+06	6.19E+06	1.99	12.00
	5	4.89E+06	52.10	3.86E+06	6.20E+06	2.02*	12.00
	10	4.93E+06	52.30	3.89E+06	6.23E+06	2*	11.90
	15	4.90E+06	52.00	3.86E+06	6.22E+06	2.01*	12.10
	20	5.00E+06	51.90	3.93E+06	6.36E+06	1.97*	11.90
2	2	5.25E+06	52.10	4.14E+06	6.66E+06	1.88*	12.00
	5	5.25E+06	52.30	4.16E+06	6.64E+06	1.88*	11.90
	10	5.26E+06	52.30	4.17E+06	6.65E+06	1.87*	12.00
	15	5.28E+06	52.00	4.16E+06	6.70E+06	1.87*	12.00
	20	5.32E+06	52.30	4.21E+06	6.73E+06	1.85*	12.00
REPEAT							
4	2	4.65E+06	52.20	3.67E+06	5.89E+06	2.08	11.90
	5	4.84E+06	52.20	3.83E+06	6.13E+06	2.04*	12.00
	10	4.80E+06	52.10	3.80E+06	6.09E+06	2.05*	12.00
	15	4.80E+06	52.40	3.80E+06	6.06E+06	2.05*	12.00
	20	4.74E+06	52.10	3.74E+06	6.01E+06	2.08*	12.10
2	2	5.54E+06	51.80	4.35E+06	7.05E+06	1.78*	12.00
	5	5.48E+06	51.70	4.30E+06	6.99E+06	1.8*	11.90
	10	5.50E+06	52.00	4.34E+06	6.98E+06	1.79*	11.90
	15	5.51E+06	51.80	4.33E+06	7.01E+06	1.79*	12.00
	20	5.49E+06	51.80	4.32E+06	6.99E+06	1.79*	12.00

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude limit was used.

TEMPERATURE 70° C

AC-20 + 14% COARSE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (⁰C)
2	2	3.84E+03	72.80	4.02E+03	3.67E+03	2.03	70.00
	5	3.91E+03	72.90	4.09E+03	3.74E+03	4.93	69.90
	10	3.93E+03	73.60	4.10E+03	3.77E+03	10.22	69.90
	15	3.74E+03	74.10	3.89E+03	3.60E+03	15.38	70.10
	20	3.69E+03	74.90	3.81E+03	3.56E+03	20.33	69.90
1	2	3.86E+03	71.10	4.07E+03	3.65E+03	2.04	70.10
	5	3.90E+03	72.10	4.10E+03	3.71E+03	5.04	70.00
	10	4.01E+03	72.60	4.20E+03	3.83E+03	10.00	69.90
	15	3.89E+03	73.00	4.07E+03	3.72E+03	15.12	70.00
	20	3.73E+03	74.60	3.86E+03	3.60E+03	20.29	70.00
REPEAT							
2	2	3.89E+03	72.80	4.08E+03	3.72E+03	1.98	70.00
	5	3.82E+03	73.90	4.00E+03	3.67E+03	4.97	70.00
	10	3.76E+03	74.20	3.90E+03	3.61E+03	10.15	70.00
	15	3.69E+03	74.90	3.82E+03	3.56E+03	15.38	70.10
	20	3.61E+03	75.40	3.73E+03	3.49E+03	20.29	70.00
1	2	4.20E+03	71.20	4.44E+03	3.98E+03	1.96	70.00
	5	4.03E+03	71.60	4.25E+03	3.82E+03	5.00	70.00
	10	3.99E+03	72.60	4.18E+03	3.81E+03	10.05	69.90
	15	3.93E+03	73.40	4.10E+03	3.77E+03	15.26	69.90
	20	3.86E+03	74.30	4.01E+03	3.72E+03	20.55	69.90

TEMPERATURE 42° C

AC-20 + 14% COARSE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
2	2	6.61E+04	55.30	8.05E+04	5.43E+04	1.99	42.00
	5	6.72E+04	55.40	8.17E+00	5.53E+04	4.81*	42.00
	10	6.68E+04	55.30	8.11E+04	5.49E+04	4.84*	42.00
	15	6.66E+04	55.10	8.11E+04	5.46E+04	4.85*	42.00
	20	6.71E+04	55.40	8.15E+04	5.52E+04	4.81*	41.90
1	2	6.51E+04	55.40	7.91E+04	5.36E+04	1.96	42.00
	5	6.51E+04	55.30	7.92E+04	5.35E+04	4.95*	42.00
	10	6.54E+04	55.50	7.94E+04	5.39E+04	4.93*	42.00
	15	6.51E+04	55.20	7.93E+04	5.34E+04	4.96*	41.90
	20	6.48E+04	55.60	7.85E+04	5.34E+04	4.98*	42.00
REPEAT							
2	2	7.17E+04	54.60	8.79E+04	5.84E+04	2.01	42.00
	5	7.12E+04	54.70	8.73E+04	5.81E+04	4.53*	42.00
	10	7.12E+04	54.50	8.74E+04	5.79E+04	4.54*	42.00
	15	7.14E+04	54.70	8.75E+04	5.83E+04	4.52*	42.00
	20	7.11E+04	54.30	8.76E+04	5.77E+04	4.54*	42.00
1	2	7.73E+04	54.10	9.55E+04	6.26E+04	1.99	42.00
	5	7.72E+04	53.90	9.55E+04	6.23E+04	4.18*	42.00
	10	7.75E+04	54.10	9.56E+04	6.27E+04	4.17*	42.00
	15	7.65E+04	54.00	9.45E+04	6.19E+04	4.22*	42.00
	20	7.65E+04	54.00	9.46E+04	6.19E+04	4.22*	42.00

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

TEMPERATURE 12° C

AC-20 +14 % COARSE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
4	2	5.66E+06	48.20	4.22E+06	7.60E+06	1.74*	11.90
	5	5.80E+06	47.80	4.30E+06	7.83E+06	1.7*	12.10
	10	5.81E+06	47.70	4.30E+06	7.86E+06	1.7*	11.90
	15	5.77E+06	48.10	4.30E+06	7.76E+06	1.71*	12.00
	20	5.75E+06	48.00	4.28E+06	7.74E+06	1.72*	12.00
2	2	5.50E+06	48.40	4.11E+06	7.36E+06	1.79*	12.00
	5	5.00E+06	48.90	3.77E+06	6.64E+06	1.97*	12.00
	10	5.50E+06	48.60	4.13E+06	7.34E+06	1.79*	11.90
	15	5.59E+06	48.20	4.17E+06	7.50E+06	1.76*	12.00
	20	5.46E+06	48.70	4.10E+06	7.27E+06	1.81*	12.00
REPEAT							
4	2	6260000	46.80	4560000	8.59E+06	1.58*	12.00
	5	6.30E+06	46.60	4.58E+06	8.67E+06	1.57*	11.90
	10	6.30E+06	46.60	4.58E+06	8.67E+06	1.56*	12.10
	15	6.35E+06	46.80	4.63E+06	8.71E+06	1.55*	12.00
	20	6.40E+06	46.70	4.66E+06	8.80E+06	1.54*	12.10
2	2	6.03E+06	47.80	4.47E+06	8.14E+06	1.63*	12.10
	5	5.99E+06	47.50	4.42E+06	8.13E+06	1.64*	11.90
	10	6.16E+06	47.50	4.53E+06	8.36E+06	1.6*	12.10
	15	6.04E+06	48.00	4.49E+06	8.13E+06	1.63*	12.00
	20	5.97E+06	48.10	4.44E+06	8.02E+06	1.65*	11.90

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude limit was used.

TEMPERATURE 70° C

AC-20 + 14% FINE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (^{0}C)
2	2	3.77E+03	73.80	3.93E+03	3.62E+03	2.00	69.90
	5	3.94E+03	74.10	4.09E+03	3.79E+03	4.94	70.00
	10	3.97E+03	74.50	4.12E+03	3.82E+03	10.12	70.00
	15	3.81E+03	75.20	3.94E+03	3.68E+03	15.38	70.10
	20	3.66E+03	75.40	3.78E+03	3.54E+03	20.53	70.00
1	2	3.31E+03	76.30	3.41E+03	3.22E+03	1.92	70.10
	5	3.07E+03	76.30	3.16E+03	2.98E+03	5.16	70.00
	10	3.15E+03	76.30	3.24E+03	3.06E+03	10.00	70.00
	15	3.06E+03	76.40	3.15E+03	2.97E+03	15.11	70.00
	20	3.19E+03	75.80	3.29E+03	3.09E+03	20.94	70.00
REPEAT							
2	2	3.31E+03	75.10	3.45E+03	3.20E+03	2.03	70.00
	5	3.38E+03	75.50	3.50E+03	3.27E+03	4.98	70.00
	10	3.28E+03	75.90	3.38E+03	3.18E+03	10.09	69.90
	15	3.20E+03	76.70	3.28E+03	3.11E+03	15.13	70.10
	20	3.14E+03	76.70	3.23E+03	3.05E+03	20.27	70.00
1	2	3.64E+03	74.30	3.78E+03	3.50E+03	1.98	70.10
	5	3.59E+03	74.60	3.72E+03	3.46E+03	5.04	70.00
	10	3.53E+03	75.50	3.74E+03	3.42E+03	10.02	70.00
	15	3.45E+03	75.90	3.56E+03	3.35E+03	14.95	69.90
	20	3.32E+03	76.50	3.42E+03	3.23E+03	20.96	69.90

TEMPERATURE 42° C

AC-20 + 14 % FINE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (⁰C)
2	2	7.89E+04	55.70	9.55E+04	6.52E+04	2.05	42.00
	5	7.89E+04	56.10	9.51E+04	6.55E+04	4.09*	42.00
	10	7.92E+04	56.10	9.53E+04	6.57E+04	4.08*	41.90
	15	7.89E+04	56.10	9.49E+04	6.55E+04	4.1*	42.10
	20	7.92E+04	56.00	9.56E+04	6.56E+04	4.08*	42.10
1	2	6.68E+04	55.70	8.08E+04	5.52E+04	2.05	42.00
	5	6.68E+04	55.80	8.07E+04	5.52E+04	4.84*	42.10
	10	6.65E+04	56.10	8.01E+04	5.52E+04	4.86*	42.00
	15	6.75E+04	55.70	8.17E+04	5.57E+04	4.78*	42.10
	20	3.42E+07	8.10	2.42E+08	4.82E+06	0.01	42.00
REPEAT							
2	2	8.19E+04	55.60	9.93E+04	6.76E+04	2.01	42.00
	5	7.81E+04	56.10	9.43E+04	6.48E+04	4.13*	42.10
	10	7.73E+04	56.00	9.32E+04	6.41E+04	4.18*	42.00
	15	7.50E+04	56.10	9.04E+04	6.22E+04	4.31*	42.00
	20	7.48E+04	56.20	9.00E+04	6.21E+04	4.32*	42.00
1	2	6.75E+04	55.80	8.17E+04	5.58E+04	2.00	42.00
	5	6.72E+04	55.90	8.12E+04	5.56E+04	4.8*	42.10
	10	6.72E+04	55.90	8.11E+04	5.56E+04	4.8*	42.00
	15	6.61E+04	55.70	8.07E+04	5.46E+04	4.85*	42.00
	20	6.64E+04	56.10	8.01E+04	5.51E+04	4.86*	41.90

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude was used.

TEMPERATURE 12° C

AC-20 + 14% FINE RUBBER

THK (MM)	STRAIN (%)	G* (Pa)	δ (DEGREES)	G */sin(δ) (Pa)	G *sin(δ) (Pa)	STRAIN (%)	TEMP (°C)
4	2	6.40E+06	46.00	4.60E+06	8.90E+06	1.54*	12.00
	5	6.64E+06	45.90	4.77E+06	9.25E+06	1.49*	12.00
	10	6.70E+06	46.00	4.82E+06	9.31E+06	1.47*	12.10
	15	6.77E+06	45.90	4.87E+06	9.43E+06	1.46*	11.90
	20	6.78E+06	45.80	4.86E+06	9.46E+06	1.46*	12.00
2	2	6.55E+06	47.30	4.82E+06	8.92E+06	1.5*	12.00
	5	6.60E+06	47.50	4.87E+06	8.96E+06	1.49*	12.00
	10	6.60E+06	47.30	4.84E+06	8.98E+06	1.5*	12.00
	15	6.63E+06	47.10	4.86E+06	9.05E+06	1.49*	12.00
	20	6.70E+06	47.30	4.92E+06	9.12E+06	1.47*	12.00
REPEAT							
4	2	6.39E+06	47.20	4.68E+06	8.71E+06	1.54*	11.80
	5	6.38E+06	47.20	4.69E+06	8.70E+06	1.55*	11.80
	10	6.38E+06	47.40	4.70E+06	8.67E+06	1.55*	11.90
	15	6.41E+06	47.50	4.73E+06	8.70E+06	1.54*	12.00
	20	6.45E+06	47.50	4.75E+06	8.75E+06	1.53*	12.00
2	2	6.26E+06	47.40	4.60E+06	8.51E+06	1.58*	11.90
	5	6.29E+06	47.50	4.64E+06	8.53E+06	1.57*	12.00
	10	6.35E+06	47.30	4.66E+06	8.64E+06	1.55*	11.90
	15	6.34E+06	47.20	4.65E+06	8.64E+06	1.55*	12.00
	20	6.35E+06	47.50	4.69E+06	8.62E+06	1.55*	12.00

* target strain value exceeds maximum stress limit value (instrument limitation), therefore maximum stress amplitude limit was used.

Appendix B1

Coefficients for Dynamic Frequency Sweep Curves

Coefficients for the Dynamic Frequency Sweep Curves

Equation form: $G^*/\sin\delta = a^*(\text{Frequency})^b$

Table B1-1 AC-20 Modified Binders - Unaged

	AC-20			AC-20+7%CR			AC-20+14%CR			AC-20+7%FR			AC-20+14%FR		
TEMP.	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
76	222.32	0.967	1	536.67	0.9293	0.9996	1091.5	0.8775	0.9988	529.64	0.9374	0.9996	1163.3	0.8934	0.999
70	431.5	0.9493	0.9998	991.26	0.9048	0.9993	2085.3	0.8461	0.9986	1051.1	0.9123	0.9993	2205.3	0.8577	0.9985
64	852.9	0.9352	0.9997	2019.7	0.8715	0.999	4127.2	0.7971	0.9981	2011.8	0.8842	0.9991	4337.1	0.8164	0.9982
58	1904.8	0.9058	0.9997	4485.3	0.8285	0.9986	8567.6	0.7441	0.9979	4351.7	0.8406	0.9989	9176	0.7619	0.9977
52	4243.9	0.8877	0.9995	9270.9	0.7885	0.9989	17133	0.7017	0.9982	9074.7	0.8083	0.9987	18629	0.7143	0.9978
42	18659	0.8427	0.9996	33901	0.7368	0.9995	54980	0.6497	0.9996	33774	0.7421	0.9991	63323	0.6603	0.9992
30	132778	0.7909	0.9999	231771	0.6745	0.9999	326647	0.6185	0.9997	151124	0.6981	0.9998	--	--	--
24	382466	0.7529	0.9997	575043	0.6591	1	746811	0.6124	0.9999	377192	0.6665	0.9998	--	--	--
12	4.00E+06	0.701	0.9999	5.00E+06	0.6278	1	5.00E+06	0.5916	0.9999	3.00E+06	0.6208	0.9989	--	--	--
6	1.00E+07	0.6733	1	1.00E+07	0.6139	0.9995	1.00E+07	0.5894	0.9997	1.00E+07	0.6273	1	--	--	--

Table B1-2 AC-20 Modified Binders - RTFO Aged

	AC-20			AC-20+7%CR			AC-20+14%CR			AC-20+7%FR			AC-20+14%FR		
TEMP.	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
76	572.44	0.9271	0.9996	1522.9	0.8262	0.9987	3701.4	0.7384	0.9977	1229	0.851	0.9991	2588.2	0.7793	0.9985
70	1142.5	0.9002	0.9995	2869.2	0.7846	0.9985	6630	0.6903	0.9975	2327.7	0.8157	0.9989	4861.6	0.7356	0.9981
64	2336.2	0.8738	0.9994	5456.7	0.743	0.9988	12177	0.6503	0.9983	4765.6	0.7788	0.9988	9005.6	0.6917	0.9983
58	5121.1	0.8411	0.9994	11256	0.704	0.9991	22057	0.6001	0.9989	9759.4	0.7338	0.9991	16610	0.6446	0.9988
52	11575	0.8136	0.9994	21935	0.6834	0.9992	40219	0.5717	0.9997	19738	0.7087	0.9989	30204	0.6181	0.9991
42	48613	0.7744	0.9997	71586	0.6496	1	116002	0.5475	1	65457	0.6696	0.9999	34261	0.7629	0.9993
30	335476	0.702	0.9998	479942	0.6137	0.9999	479942	0.6137	0.9999	421275	0.628	0.9999	426772	0.5431	0.9976
24	884140	0.6692	0.9997	1000000	0.6007	0.9999	1000000	0.6007	0.9999	1000000	0.6141	0.9998	876703	0.5564	0.9998
12	7.00E+06	0.6343	0.9997	8.00E+06	0.5803	0.9999	8.00E+06	0.5803	0.9999	7.00E+06	0.6045	0.999	3.00E+06	0.6318	0.9991
6	2.00E+07	0.6257	1	2.00E+07	0.5468	0.9996	2.00E+07	0.5468	0.9996	1.00E+07	0.5553	1	1.00E+07	0.6388	0.9998

Coefficients for the Dynamic Frequency Sweep Curves (contd.)

Equation form: $G^*/\sin\delta = a^*(\text{Frequency})^b$

Table B1-3 AC-10 Modified Binders - Unaged

	AC-10			AC-10+7%CR			AC-10+14%CR			AC-10+7%FR			AC-10+14%FR		
TEMP	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
76	113.85	0.9699	1	227.99	0.9578	0.9995	1097.4	0.7898	0.9991	204.53	0.9665	0.9999	642.56	0.91	0.9991
70	200.82	0.963	1	421.09	0.9359	0.9998	1858.9	0.7525	0.9987	376.4	0.9415	0.9998	1187.6	0.8782	0.9989
64	380.65	0.9539	0.9998	811.39	0.9196	0.9996	3305.5	0.7045	0.9988	709.23	0.9325	0.9996	2219.7	0.8412	0.9985
58	817.7	0.9344	0.9997	1877.6	0.8652	0.9995	5924.5	0.6645	0.999	1472.7	0.905	0.9994	4446.9	0.7818	0.9981
52	1715.8	0.9171	0.9996	3781.5	0.8602	0.9989	10402	0.636	0.9992	3027.7	0.8801	0.9992	8412.3	0.7476	0.9979
42	6884	0.8733	0.9996	13736	0.7929	0.9988	28106	0.604	0.9999	11282	0.8198	0.9989	25626	0.6761	0.9985
30	78795	0.8123	0.9999	105728	0.7092	1	152730	0.6273	0.9988	93534	0.7468	0.9995	151274	0.628	0.9993
24	177017	0.7813	0.9998	257466	0.6861	0.9999	350696	0.6151	0.9994	245085	0.6974	0.9998	343628	0.6087	0.9997
12	7.14E+05	0.7239	0.9994	2.00E+06	0.6425	0.9999	2.00E+06	0.5956	0.9995	2.00E+06	0.6505	0.9997	2.00E+06	0.6	0.9997
6	1.00E+06	0.7093	0.9994	4.00E+06	0.6348	0.9999	3.00E+06	0.5705	1	3.00E+06	0.6445	0.9999	5.00E+06	0.5814	1

Table B1-4 AC-10 Modified Binders - RTFO Aged

	AC-10			AC-10+7%CR			AC-10+14%CR			AC-10+7%FR			AC-10+14%FR		
TEMP	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
76	186.93	0.9754	0.9999	673.41	0.8781	0.999	2155.3	0.7116	0.9982	572.23	0.902	0.9993	1445.5	0.8084	0.9983
70	370.42	0.9482	0.9998	1306.1	0.8373	0.9986	3733.3	0.6644	0.9983	1108.1	0.8639	0.9988	2607.5	0.7633	0.9982
64	755.06	0.9263	0.9996	2583.8	0.7919	0.9985	6521.9	0.6209	0.9988	2130.9	0.8242	0.9987	4822.9	0.7144	0.9981
58	1742.7	0.8955	0.9993	5090.7	0.7484	0.9987	11230	0.5889	0.9994	4548.1	0.7791	0.9986	8996	0.6673	0.9984
52	3889.2	0.8621	0.9993	10058	0.7132	0.9991	19502	0.5671	0.9998	9366.3	0.7421	0.9985	16604	0.6315	0.9987
42	16448	0.8085	0.9995	34163	0.6697	0.9999	53150	0.5486	0.9997	32827	0.6825	0.9996	48844	0.5836	0.9998
30	137757	0.7336	0.9999	206004	0.6422	0.9996	266856	0.5658	0.9992	200611	0.6469	0.9997	229780	0.5688	0.998
24	368308	0.7015	0.9996	496768	0.623	0.9999	572236	0.566	0.9988	477790	0.6312	1	442199	0.5722	0.9996
12	3.00E+06	0.6484	0.9999	4.00E+06	0.5903	0.9997	3.00E+06	0.5591	0.9992	3.00E+06	0.6115	0.9996	3.00E+06	0.5496	0.9999
6	7.00E+06	0.6156	0.9999	9.00E+06	0.5728	1	8.00E+06	0.5305	1	9.00E+06	0.5853	1	8.00E+06	0.5454	1

Coefficients for the Dynamic Frequency Sweep Curves

Equation form: $G^*/\sin\delta = a^*(\text{Frequency})^b$

Table B1-5 PG Graded Modified Binders - Unaged

	PG 64-22			PG 70-22			PG 76-22 Multi-grade			PG 76-22 SBS			PG 76-22 SBR		
TEMP	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
76	150.62	1.0111	1	216.02	0.9874	1	784.88	0.8081	0.9999	960.68	0.8375	0.9995	786.67	0.8888	0.9994
70	298	0.98	0.9999	443.45	0.9645	0.9998	1338.3	0.8232	0.9999	1799.2	0.8097	0.9992	1460.9	0.8616	0.9992
64	604.52	0.9594	0.9998	895.99	0.9456	0.9997	2512.9	0.8192	0.9999	3333.7	0.7811	0.9994	2852.7	0.8326	0.999
58	1326.3	0.9379	0.9996	1996.5	0.921	0.9996	5312.7	0.8198	0.9998	6550.6	0.7507	0.9996	5736.7	0.8008	0.9989
52	3323.8	0.9099	0.9995	4673.4	0.8957	0.9996	11691	0.8044	0.9997	13264	0.7303	0.9997	12393	0.7656	0.9988
42	14582	0.863	0.9997	21261	0.857	0.9998	49619	0.7758	0.9998	44916	0.7091	1	41512	0.7165	0.9993
30	--	--	--	206015	0.7814	0.9998	--	--	--	343520	0.6814	0.9999	--	--	--
24	--	--	--	605123	0.7473	0.9997	--	--	--	752226	0.6609	0.9997	--	--	--
12	--	--	--	6.00E+06	0.7287	0.9997	1.00E+07	0.6716	0.9925	4.00E+06	0.6179	0.9996	--	--	--
6	--	--	--	2.00E+07	0.689	1	--	--	--	5.00E+06	0.6235	0.9997	--	--	--

Table B1-6 PG Graded Modified Binders - RTFO Aged

	PG 64-22			PG 70-22			PG 76-22 Multi-grade			PG 76-22 SBS			PG 76-22 SBR		
TEMP	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
76	456.32	0.9515	0.9997	692.23	0.9317	0.9996	946.85	0.8674	0.9996	1926.8	0.7614	0.9996	2118.5	0.8246	0.999
70	982.77	0.9206	0.9995	1448.1	0.9049	0.9994	1898.6	0.8493	0.9995	3598.6	0.7325	0.9997	3878.5	0.7965	0.999
64	2069.8	0.8912	0.9994	3038.7	0.8768	0.9994	--	--	--	6962.9	0.7086	0.9999	7601.6	0.7644	0.9989
58	4590.3	0.8608	0.9993	6624.4	0.8436	0.9994	8841.2	0.8003	0.9994	13522	0.6895	1	14040	0.7317	0.9988
52	10436	0.8282	0.9994	15485	0.8123	0.9995	19386	0.7759	0.9995	27201	0.6753	1	27739	0.655	0.9988
42	46959	0.7898	0.9998	69913	0.7821	0.9999	84688	0.7369	0.9999	93603	0.6594	1	87557	0.6352	0.9989
30	276014	0.6878	0.9993	622962	0.6893	0.9997	643386	0.6401	0.9992	--	--	--	--	--	--
24	730485	0.6515	0.9986	2000000	0.6973	0.9995	1000000	0.6232	0.9991	--	--	--	--	--	--
12	7.00E+06	0.6136	0.9999	2.00E+07	0.6707	1	1.00E+07	0.5789	1	--	--	--	--	--	--
6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Appendix B2

Values of G*sinδ @ 10rad./sec (1.59 Hz)

Table B2-1 AC-20 Modified Binders - Unaged, G*/Sin(δ) (kPa) at 1.59 Hz

TEMP. °C	BINDER TYPE				
	AC-20 P	AC-20 +7 % CR	AC-20 +14% CR	AC-20 +7 % FR	AC-20 +14% FR
76	3.48E-01	8.26E-01	1.64E+00	8.18E-01	1.76E+00
70	6.70E-01	1.51E+00	3.09E+00	1.60E+00	3.28E+00
64	1.32E+00	3.03E+00	5.97E+00	3.03E+00	6.33E+00
58	2.90E+00	6.59E+00	1.21E+01	6.43E+00	1.31E+01
52	6.41E+00	1.34E+01	2.37E+01	1.32E+01	2.59E+01
42	2.76E+01	4.77E+01	7.43E+01	4.76E+01	8.60E+01
30	1.92E+02	3.17E+02	4.35E+02	2.09E+02	--
24	5.42E+02	7.81E+02	9.92E+02	5.14E+02	--
12	5.54E+03	6.69E+03	6.58E+03	4.00E+03	--
6	1.37E+04	1.33E+04	1.31E+04	1.34E+04	--
					--

Table B2-2 AC-20 Modified Binders - RTFO Aged, G*/Sin(δ) (kPa) at 1.59 Hz

TEMP. °C	BINDER TYPE				
	AC-20 P	AC-20 +7 % CR	AC-20 +14% CR	AC-20 +7 % FR	AC-20 +14% FR
76	8.80E-01	2.23E+00	5.21E+00	1.82E+00	3.71E+00
70	1.73E+00	4.13E+00	9.13E+00	3.40E+00	6.84E+00
64	3.50E+00	7.70E+00	1.65E+01	6.84E+00	1.24E+01
58	7.56E+00	1.56E+01	2.91E+01	1.37E+01	2.24E+01
52	1.69E+01	3.01E+01	5.24E+01	2.74E+01	4.02E+01
42	6.96E+01	9.68E+01	1.50E+02	8.93E+01	4.88E+01
30	4.65E+02	6.38E+02	6.38E+02	5.64E+02	5.49E+02
24	1.21E+03	1.32E+03	1.32E+03	1.33E+03	1.13E+03
12	9.39E+03	1.05E+04	1.05E+04	9.26E+03	4.02E+03
6	2.67E+04	2.58E+04	2.58E+04	1.29E+04	1.34E+04

Table B2-3 AC-10 Modified Binders - Unaged, G*/Sin(δ) (kPa) at 1.59 Hz

TEMP. °C	BINDER TYPE AC-10 P	AC-10 +7 % CR	AC-10 +14% CR	AC-10 +7 % FR	AC-10 +14% FR
76	1.79E-01	3.55E-01	1.58E+00	3.20E-01	3.20E-01
70	3.14E-01	6.50E-01	2.64E+00	5.82E-01	5.82E-01
64	5.92E-01	1.24E+00	4.58E+00	1.09E+00	1.09E+00
58	1.26E+00	2.80E+00	8.06E+00	2.24E+00	2.24E+00
52	2.36E+00	5.64E+00	1.40E+01	4.55E+00	4.55E+00
42	1.03E+01	1.98E+01	3.72E+01	1.65E+01	1.65E+01
30	1.15E+02	1.47E+02	2.04E+02	1.32E+02	1.32E+02
24	2.54E+02	3.54E+02	4.66E+02	3.39E+02	3.39E+02
12	9.99E+02	2.69E+03	2.64E+03	2.70E+03	2.70E+03
6	1.39E+03	5.37E+03	3.91E+03	4.05E+03	4.05E+03

Table B2-4 AC-10 Modified Binders - RTFO Aged, G*/Sin(δ) (kPa) at 1.59 Hz

TEMP. °C	BINDER TYPE AC-10 P	AC-10 + 7 % CR	AC-10 + 14% CR	AC-10 + 7 % FR	AC-10 + 14% FR
76	2.94E-01	1.01E+00	8.26E+00	8.69E-01	2.10E+00
70	5.75E-01	1.93E+00	1.35E+01	1.65E+00	3.71E+00
64	1.16E+00	3.73E+00	2.23E+01	3.12E+00	6.72E+00
58	2.64E+00	7.20E+00	3.66E+01	6.53E+00	1.23E+01
52	5.80E+00	1.40E+01	6.13E+01	1.32E+01	2.23E+01
42	2.39E+01	4.66E+01	1.53E+02	4.50E+01	6.40E+01
30	1.94E+02	2.77E+02	7.06E+02	2.71E+02	2.99E+02
24	5.10E+02	6.63E+02	1.25E+03	6.40E+02	5.77E+02
12	4.05E+03	5.26E+03	7.50E+03	3.98E+03	3.87E+03
6	9.31E+03	1.17E+04	1.23E+04	1.18E+04	1.03E+04

Table B2-5 PG Binders - Unaged, G*/Sin(δ) (kPa) at 1.59 Hz

TEMP. °C	BINDER TYPE				
	PG 64	PG 70	PG 76 Multi-grade	PG 76 SBS	PG 76 SBR
76	2.4E-01	3.41E-01	1.14E+00	1.42E+00	1.19E+00
70	4.69E-01	6.94E-01	1.96E+00	2.62E+00	2.18E+00
64	9.43E-01	1.39E+00	3.67E+00	4.79E+00	4.20E+00
58	2.05E+00	3.06E+00	7.77E+00	9.28E+00	8.32E+00
52	5.07E+00	7.08E+00	1.70E+01	1.86E+01	1.77E+01
42	2.18E+01	3.16E+01	7.11E+01	6.24E+01	5.79E+01
30	--	2.96E+02	--	4.71E+02	--
24	--	8.56E+02	--	1.02E+03	--
12	--	8.41E+03	1.37E+04	5.33E+03	--
6	--	2.75E+04	--	6.68E+03	--
	--	--	--	--	--

Table B2-6 PG Binders - RTFO Aged, G*/Sin(δ) (kPa) at 1.59 Hz

TEMP. °C	BINDER TYPE				
	PG 64	PG 70	PG 76 Multi-grade	PG 76 SBS	PG 76 SBR
76	7.09E-01	1.07E+00	1.42E+00	2.74E+00	3.11E+00
70	1.51E+00	2.20E+00	2.82E+00	5.05E+00	5.61E+00
64	3.13E+00	4.56E+00	--	9.67E+00	1.08E+01
58	6.84E+00	9.80E+00	1.28E+01	1.86E+01	1.97E+01
52	1.53E+01	2.26E+01	2.78E+01	3.72E+01	3.83E+01
42	6.77E+01	1.00E+02	1.19E+02	1.27E+02	1.18E+02
30	3.80E+02	8.58E+02	8.66E+02	--	--
24	9.88E+02	2.76E+03	1.34E+03	--	--
12	9.30E+03	2.73E+04	1.31E+04	--	--
6	--	2.75E+04	--	--	--
	--	--	--	--	--

Appendix B3

Coefficients for Regression Analysis for the Dynamic Frequency Sweep Curves

Table B3-1 -- Regression coefficients for the dynamic frequency sweep data - AC-20 modified binders

Regression form: $\ln G^* = a + b \cdot \ln(Temp) + c \cdot \ln(Freq) + d \cdot \ln(Temp) \cdot \ln(Freq) + e \cdot \{\ln(Temp)\}^2 + f \cdot \{\ln(Freq)\}^2$

G* = dynamic shear moduli, Pa
Temp = test temperature between 6°C and 76°C
Freq = test frequency between 0.1 Hz and 20 Hz
Ln = natural logarithm
a...f = regression coefficients
R^2 = coefficient of determination

Aging	Binder Type	a	b	c	d	e	f	R^2
Unaged	AC-20 Processed	9.545	6.467	0.160	0.186	-1.713	-0.011	0.999
	AC-20+7% CR	9.681	6.226	0.002	0.206	-1.615	-0.015	0.999
	AC-20 +14% CR	10.132	5.767	0.023	0.183	-1.493	-0.014	0.999
	AC-20 +7% FR	10.504	5.348	-0.062	0.225	-1.450	-0.019	0.999
	AC-20 +14% FR	13.430	0.043	-0.436	0.286	-0.307	0.019	0.731
RTFO Aged	AC-20 Processed	7.790	7.755	-0.050	0.222	-1.865	-0.013	0.999
	AC-20+7% CR	10.616	5.739	0.087	0.158	-1.499	-0.010	0.999
	AC-20 +14% CR	13.314	3.726	0.367	0.064	-1.132	-0.008	0.999
	AC-20 +7% FR	9.132	6.623	0.067	0.170	-1.634	-0.014	0.999
	AC-20 +14% FR	11.236	4.804	0.044	0.153	-1.286	-0.013	0.999
PAV Aged	AC-20 Processed	--	--	--	--	--	--	--
	AC-20+7% CR	5.706	8.525	-0.237	0.215	-1.823	-0.009	0.996
	AC-20 +14% CR	12.124	4.466	0.191	0.083	-1.189	-0.001	0.999
	AC-20 +7% FR	9.090	6.710	-0.197	0.206	-1.587	-0.009	0.998
	AC-20 +14% FR	11.499	5.016	-0.013	0.146	-1.301	-0.002	0.997

Table B3-2 -- Regression coefficients for the dynamic frequency sweep data - AC-10 modified binders

Regression form: $LnG^* = a + b*Ln(Temp) + c*Ln(Freq) + d*Ln(Temp)*Ln(Freq) + e*\{Ln(Temp)\}^2 + f*\{Ln(Freq)\}^2$

G* = dynamic shear moduli, Pa
Temp = test temperature between 6°C and 76°C
Freq = test frequency between 0.1 Hz and 20 Hz
Ln = natural logarithm
a...f = regression coefficients
R^2 = coefficient of determination

Aging	Binder Type	a	b	c	d	e	f	R^2
Unaged	AC-10 Processed	5.838	7.877	0.394	0.134	-1.883	-0.012	0.997
	AC-10+7% CR	9.427	5.883	0.185	0.174	-0.019	-1.567	0.999
	AC-10 +14% CR	10.682	4.575	0.394	0.071	-1.256	-0.009	0.999
	AC-10 +7% FR	8.670	6.382	0.150	0.186	-1.653	-0.017	0.999
	AC-10 +14% FR	11.462	4.357	0.250	0.132	-1.264	-0.015	0.999
RTFO Aged	AC-10 Processed	8.586	6.969	0.062	0.201	-1.765	-0.014	0.999
	AC-10+7% CR	10.535	5.354	0.121	0.154	-1.431	-0.011	0.999
	AC-10 +14% CR	12.307	3.836	0.394	0.051	-1.129	-0.002	0.999
	AC-10 +7% FR	10.192	5.623	0.079	0.170	-1.482	-0.013	0.999
	AC-10 +14% FR	12.212	3.876	0.171	0.122	-1.142	-0.012	0.999
PAV Aged	AC-10 Processed	12.001	3.621	0.378	0.109	-1.098	-0.024	0.979
	AC-10+7% CR	10.706	5.522	0.100	0.140	-1.427	0.009	0.999
	AC-10 +14% CR	12.851	3.603	0.309	0.057	-1.062	0.000	0.999
	AC-10 +7% FR	10.517	5.680	0.083	0.148	-1.464	-0.010	0.999
	AC-10 +14% FR	13.438	3.061	0.225	0.080	-0.956	-0.005	0.994

Table B3-3 -- Regression coefficients for the dynamic frequency sweep data - PG graded binders

Regression form: $LnG^* = a + b^*Ln(Temp) + c^*Ln(Freq) + d^*Ln(Temp)^*Ln(Freq) + e^*\{Ln(Temp)\}^2 + f^*\{Ln(Freq)\}^2$

G* = dynamic shear moduli, Pa
Temp = test temperature between 6°C and 76°C
Freq = test frequency between 0.1 Hz and 20 Hz
Ln = natural logarithm
a...f = regression coefficients
R^2 = coefficient of determination

Aging	Binder Type	a	b	c	d	e	f	R^2
Unaged	PG 64-22	12.582	4.597	0.197	0.178	-1.436	-0.015	0.999
	PG 70-22	9.782	6.864	0.128	0.192	-1.798	-0.012	0.999
	PG 76-22 Multi-Grade	12.247	5.213	0.378	0.105	-1.506	-0.006	0.999
	PG 76-22 SBS	7.808	7.173	0.344	0.104	-1.709	-0.008	0.999
	PG 76-22 SBR	8.376	6.877	-0.431	0.304	-1.677	-0.018	0.999
RTFO Aged	PG 64-22	7.793	7.521	-0.294	0.281	-1.808	-0.016	0.999
	PG 70-22	7.692	8.385	-0.025	0.211	-1.978	-0.012	0.999
	PG 76-22 Multi-Grade	6.362	8.829	-0.175	0.241	-2.011	-0.012	0.999
	PG 76-22 SBS	3.906	9.202	0.028	0.165	-1.933	-0.005	0.999
	PG 76-22 SBR	8.592	6.569	-0.457	0.291	-1.564	-0.018	0.998
PAV Aged	PG 64-22	1.467	11.206	-0.481	0.307	-2.258	-0.018	0.998
	PG 70-22	2.638	11.058	-0.884	0.400	-2.269	-0.021	0.999
	PG 76-22 Multi-Grade	-0.112	11.756	-1.005	0.424	-2.288	-0.011	0.991
	PG 76-22 SBS	3.300	9.705	0.032	0.152	-1.976	-0.004	0.999
	PG 76-22 SBR	-21.863	22.300	-1.032	0.417	-3.523	-0.042	0.989

Table B3-4 -- Regression coefficients for the dynamic frequency sweep data - AC-20 modified binders

Regression form: $Ln(Phase) = a + b*Ln(G^*) + c*Ln(G^*)^2 + d*Ln(G^*)^3$

G* = dynamic shear moduli, Pa
Phase = phase angle (δ),
Ln = natural logarithm
a...d = regression coefficients
R^2 = coefficient of determination

Aging	Binder Type	a	b	c	d	R^2
Unaged	AC-20 Processed	4.566	-0.017	0.000	0.000	0.987
	AC-20+7% CR	4.450	0.044	-0.010	0.000	0.982
	AC-20 +14% CR	4.450	0.044	-0.010	0.000	0.982
	AC-20 +7% FR	4.246	0.121	-0.018	0.001	0.988
	AC-20 +14% FR	2.912	0.656	-0.084	0.003	0.358
RTFO Aged	AC-20 Processed	4.574	-0.013	-0.002	0.000	0.989
	AC-20+7% CR	5.393	-0.263	0.019	-0.001	0.978
	AC-20 +14% CR	8.269	-1.058	0.087	-0.002	0.864
	AC-20 +7% FR	5.005	-0.139	0.007	0.000	0.981
	AC-20 +14% FR	5.953	-0.396	0.028	-0.001	0.968
PAV Aged	AC-20 Processed	--	--	--	--	--
	AC-20+7% CR	5.829	-0.398	0.031	-0.001	0.968
	AC-20 +14% CR	9.243	-1.362	0.115	-0.003	0.851
	AC-20 +7% FR	6.706	-0.481	0.040	-0.001	0.973
	AC-20 +14% FR	7.723	-0.909	0.074	-0.002	0.935

Table B3-5 -- Regression coefficients for the dynamic frequency sweep data - AC-10 modified binders

Regression form: $Ln(Phase) = a + b*Ln(G*) + c*Ln(G*)^2 + d*Ln(G*)^3$

G* = dynamic shear moduli, Pa
Phase = phase angle (δ),
Ln = natural logarithm
a...d = regression coefficients
R^2 = coefficient of determination

Aging	Binder Type	a	b	c	d	R^2
Unaged	AC-10 Processed	4.549	-0.014	0.000	0.000	0.980
	AC-10+7% CR	4.445	0.054	-0.011	0.000	0.988
	AC-10 +14% CR	6.315	-0.528	-0.045	-0.001	0.929
	AC-10 +7% FR	4.297	0.101	-0.015	0.000	0.989
	AC-10 +14% FR	4.969	-0.108	0.003	0.000	0.955
RTFO Aged	AC-10 Processed	4.558	-0.010	-0.002	0.000	0.992
	AC-10+7% CR	5.108	-0.181	0.012	0.000	0.978
	AC-10 +14% CR	7.198	-0.841	73.000	-0.002	0.926
	AC-10 +7% FR	4.832	-0.083	0.001	0.000	0.978
	AC-10 +14% FR	5.835	-0.382	0.027	-0.001	0.957
PAV Aged	AC-10 Processed	4.933	-0.141	0.011	0.000	0.871
	AC-10+7% CR	6.008	-0.466	0.039	-0.001	0.970
	AC-10 +14% CR	5.333	-0.282	0.028	-0.001	0.992
	AC-10 +7% FR	5.516	-0.316	0.025	-0.001	0.971
	AC-10 +14% FR	6.311	-0.655	0.060	-0.002	0.934

Table B3-6 -- Regression coefficients for the dynamic frequency sweep data - PG graded binders

Regression form: $Ln(Phase) = a + b*Ln(G*) + c*Ln(G*)^2 + d*Ln(G*)^3$

G* = dynamic shear moduli, Pa
Phase = phase angle (δ),
Ln = natural logarithm
a...d = regression coefficients
R^2 = coefficient of determination

Aging	Binder Type	a	b	c	d	R^2
Unaged	PG 64-22	4.644	-0.049	0.004	0.000	0.972
	PG 70-22	4.575	-0.018	0.000	0.000	0.992
	PG 76-22 Multi-Grade	4.076	0.065	-0.004	0.000	0.973
	PG 76-22 SBS	5.149	-0.229	0.020	-0.001	0.985
	PG 76-22 SBR	3.995	0.214	-0.031	0.001	0.983
RTFO Aged	PG 64-22	4.441	0.029	-0.005	0.000	0.992
	PG 70-22	4.623	-0.026	-0.001	0.000	0.991
	PG 76-22 Multi-Grade	4.425	0.010	-0.003	0.000	0.990
	PG 76-22 SBS	5.888	-0.506	0.051	-0.002	0.925
	PG 76-22 SBR	4.583	0.001	-0.007	0.000	0.955
PAV Aged	PG 64-22	5.333	-0.282	0.028	-0.001	0.992
	PG 70-22	4.527	0.000	-0.004	0.000	0.983
	PG 76-22 Multi-Grade	4.406	0.009	-0.001	0.000	0.964
	PG 76-22 SBS	5.756	-0.462	0.004	-0.001	0.853
	PG 76-22 SBR	5.426	-0.314	0.030	-0.001	0.933

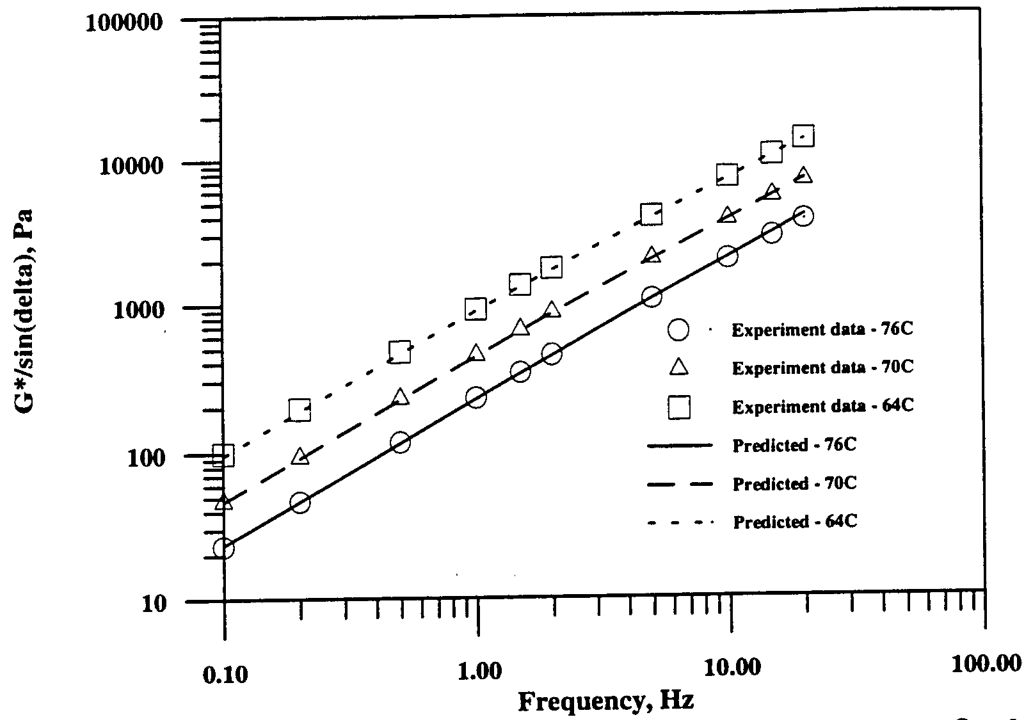

Figure B3-1 -- AC-20 processed, actual versus predicted G*/sinδ values

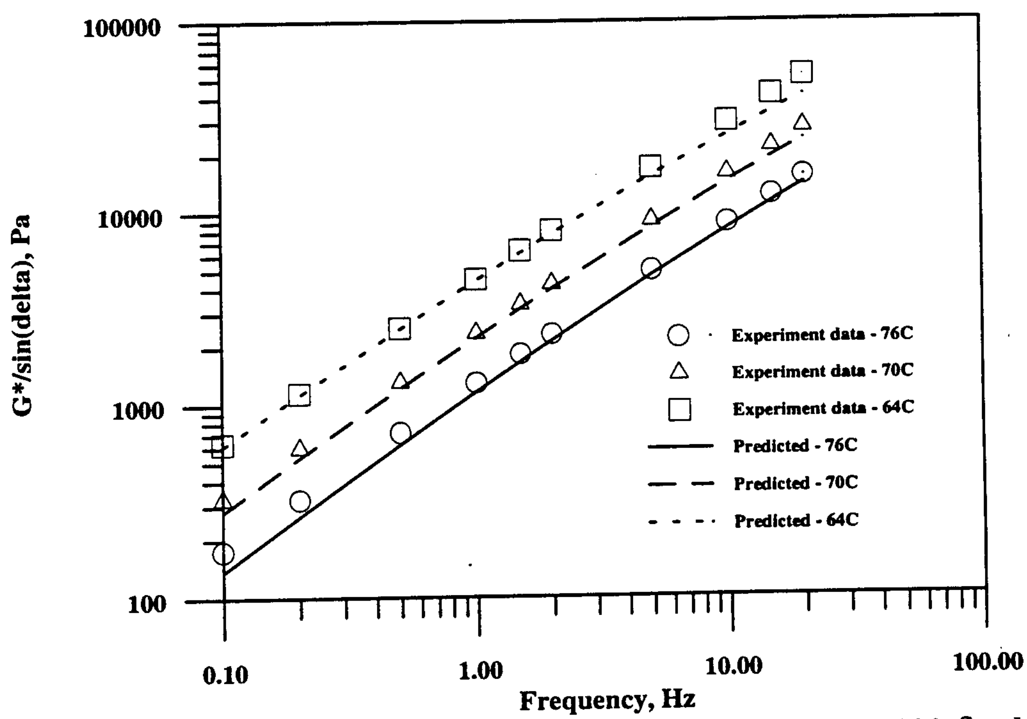

Figure B3-2 -- AC-20+14% CR, actual versus predicted G*/sinδ values

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